Development of an instrument for monitoring and data logging illuminance levels for interior daylighting applications

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Abstract

Daylighting is fast emerging globally as a popular clean energy technology to compliment artificial electrical lighting. Unlike traditional artificial lighting, however, the variability of the sun due to geographical, geometrical and climatic variations presents a major challenge to engineers and architects involved in daylighting system design, particularly for critical tasks such as reading.

This project evolved out of the need to be able to fully describe the performance of daylighting applications in order to aid and validate the design, improvement and installation of such systems. The primary focus of the project was to design, develop and test a system that is able to record and convey the variability of light, within an interior space, in terms of the spatial and time domains for the monitoring of daylighting applications, at a fraction of the cost of similar commercially available systems.

Several potential sensors underwent stringent selection and testing procedures to determine which would meet the project requirements. The selected Sharp GA1A2S100LY sensing device proved to be the most suitable and was developed and included in a microcontroller based system to record illumination levels at multiple locations simultaneously. The sensor was selected and developed to match the spectral sensitivity of the human eye within the range of 0-1500 lux.

The PIC18F8722 Explorer Demonstration Board manufactured by Microchip was selected to control all system operations. The board interfaces with each illuminance sensor and records the measured data, in text format in a .txt file on an SD card, in the PICtail daughter board SD card module.

The system was able to record data from 64 sensors, simultaneously, at predefined time intervals and to store it for later processing. The data was then refined and used to generate easy to interpret visual representations of the illumination characteristics of the measured area as a function of time.

The data is imported from the SD card text file to Microsoft Excel where a constant, predetermined, correction factor is applied to the data.

A MATLAB program was developed to read the corrected data from the Excel spreadsheet and give an animated display of the progression of the illumination characteristics over the period for which the measurements were taken.

Testing conducted with the system was done in an area supplied with daylight from two passive zenithal light pipes. The use of the system, under these conditions, proved effective with the system able to accurately convey the hourly, daily and seasonal variability of light within the measured area over a period of time.

Opsomming

Dagbeligting ontwikkel teen ‘n hoë pas wêreldwyd as ‘n gewilde vorm van skoon energie tegnologie. Die doel van dagbeligting is om kunsmatige elektriese beligting aan te vul. In teenstelling met tradisionele kunsmatige beligting, bied die die son ‘n verskeidenheid van groot uitdagings vir ingenieurs en argitekte betrokke in die ontwerp van ‘n dagbeligting stelsel, veral vir take van kritieke belang insluitend die vermoë om te kan lees. Uitdagings sluit in: Geografiese-, geometriese-, asook klimaatstoestand veranderlikes.

Hierdie projek het ontwikkel vanuit die behoefte om ten volle die werksverrigting van dagbeligting toepassings te kan beskryf om sodoende die ontwerp, bevordering en installering van dagbeligting stelsels te steun en te bevestig. Die hooffokus van die projek was om ‘n stelsel te ontwerp, ontwikkel en te toets wat die vermoë het om die veranderlikheid van lig, binne ‘n binneruimte, in terme van ruimtelike- en tydsdomeine op te neem en hierdie oor te dra vir die monitor van dagbeligting toepassings, teen 'n fraksie van die koste van 'n soortgelyke kommersieel beskikbare stelsel.

Verskeie moontlike sensors het streng keuring- en toetsprosedures ondergaan om te bepaal watter sensors aan die projek vereistes sal voldoen. Die sensor wat gevind was as die mees toepaslike, bepaal deur die resultate verkry vanaf die keuring- en toetsprosedures, was die Sharp GA1A2S100LY sensor toestel. Hierdie toestel was ontwikkel en ingesluit in ‘n mikroverwerker beheerstelsel om beligtingsvlakke by verskeie liggings terselfdertyd op te neem. Verder, was die sensor gekies en ontwikkel om die spektrale sensitiwiteit van die menslike oog te ewenaar, binne die reik van 0 – 1500 lux.

Die PIC18F8722 Explore Demonstration Board vervaardig deur Microchip was gekies om alle stelsel bedrywighede te beheer. Die bord kommunikeer met elke illuminansievlaksensor en neem die gemete data op, in teks formaat in ‘n .txt lêer wat dan op ‘n SD kaart gestoor word, in die PICtail Daughter Board SD kaart module.

Die stelsel kon data van 64 sensors, gelyktydig, opneem by voorafbepaalde tydsintervalle en dit dan stoor vir verdere verwerking later. Die data was dan verfyn en gebruik om maklik-om-te- interpreteer visuele voorstellings van die beligtingseienskappe van die gemete area as ‘n funksie van tyd te genereer. Die data, gestoor as ‘n .txt lêer, word ingevoer van die SD kaard in Microsoft Excel in waar ‘n konstante, voorafbepaalde regstellingsfaktor op die data toegepas word.

A MATLAB program was ontwikkel om die gekorrigeerde data te lees vanaf die Excel werkblad en ‘n geanimeerde voorstelling, van die vordering van die beligtingseienskappe oor die tydperk waarvoor die lesings geneem was, terug te voer.

Toetse uitgevoer met die stelsel was uitgevoer in ‘n vertrek, voorsien met daglig van twee passiewe “zenithal” beligtingspype. Die gebruik van die stelsel, onder hierdie kondisies, blyk effektief. Die stelsel is in staat om akkuraat die uurlikse, daaglikse, asook die seisoensveranderlikheid van lig, binne die afgemete area oor ’n tydperk van tyd, weer te gee.

Acknowledgements

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Project Description and Background

This project evolved out of an earlier project entailing the design, installation and testing of a daylighting system, for a rural South African classroom. One of the main challenges faced by daylighting systems is the variability of light in spatial and time domains with respect to the working area. In order to fully describe the performance of the system it became necessary to install a monitoring and logging system to describe those variations on an hourly, daily and seasonal basis. Inquiries were subsequently made to source the necessary instrumentation. The search was however rather disappointing as not only did the available choice seem inadequate but proved extremely expensive.

It was therefore decided to explore the possibility of designing an in-house instrument that would achieve the desired objective cost-effectively.

This project initially investigated current component technologies which sense, collect and record data for the light intensity of an illuminated area. This process allowed for a closer look at the behaviour of light within an interior space, in turn aiding the implementation, advancement and improvement of both lighting and daylighting systems.

The primary focus of the project is to design, develop and test a system that is able to measure, record and convey the variability of light within an interior space in terms of the spatial and time domains for daylighting application monitoring. The desired goal of the project is therefore to visually display the lighting conditions and lighting changes within an interior area in an easily understood and visually pleasing manner from physically recorded measurements of lighting levels at predefined locations.

The system will target a range of luminance sensitivity similar to that of the human eye. The system is to be designed from widely available off-the-shelf components where possible, following a systems engineering approach where the focus is to optimise the performance of the overall system, to achieve the system goal, while minimising cost. Compromises in time response and accuracy are expected and will be minimised where possible. The system is anticipated to be an order of magnitude less expensive than commercially available products.

1.2 Objectives

As previously stated, this project is aimed at investigating current component technologies capable of light measurement, as well as, designing, developing and testing a light metrics measurement and data collection system at a fraction of the cost of similar, commercially available products.

The objectives of the project are therefore:

- Research the properties of light and identify effective methods of light measurement.
- Identify components for light measurement with sensitivity similar to that of the human eye.
- Design a light measuring device.
- Develop and test a light measuring device.
- Design a light metrics measurement system with measurement and data storage capabilities for multiple locations within an area.
- Develop and test the complete system.

1.3 Motivation

According to (Alfstad et al. 2006), the global energy system has some major shortfalls. The overall system has proven inefficient with an efficiency of around 39%. This figure is unlikely to be raised, as major irreversibility's in the system make improvements a daunting task. In addition to this the global energy system has major environmental and social problems, both globally and locally, associated with it.

Around one-fifth (20%) of the current, global, electricity consumption is utilised for electric lighting. It has also been predicted that the demand for artificial lighting will rise by 80% by the year 2030 (POST 2010).

There has been an architectural movement towards green buildings in recent years to try and negate the irreversibility's and inefficiencies present in the energy system as well as to utilise sustainable energy to reduce artificial lighting demands. These buildings imply a sustainable design (conservation of resources, energy efficiency, renewable energies, passive design, etc.) and a healthy environment for people (air quality, non-toxic materials and occupants' health) (Alfstad et al. 2006).

At the present time there is a growing interest in the use of renewable energy sources in South Africa. There are many reasons for this growing interest, one of which is that the country has been experiencing major problems with the electricity supply versus demand, resulting in numerous power supply shortages (Dodd & McNair 2012). Other reasons include the escalating cost of electricity in South Africa and the abundance of renewable energy sources in the country.

Many buildings are utilized during daylight hours and require illumination for those inside to perform their desired tasks. This leads to a situation in which electrical consumption is at its greatest for illumination when there is also an abundance of natural light that could be utilized for illumination (Muhs 2000). A reduction in the dependency on electricity for illumination during daylight hours by utilizing natural lighting systems can lead to a sustainable design by utilizing renewable solar energy and conserving non-renewable resources.

South Africa is one of the areas in the world with the highest counts of sunny days per year with South Africa ranking 5th, according to (Osbourn n.d.), on a list of countries with the highest average sunshine per year. The rankings are based on data recorded by the World Meteorological Organization between 1961 and 1990. This makes South Africa an ideal country for the utilization of daylight illumination systems.

Daylighting systems have the potential to offer tremendous reductions in energy consumption required for electrical lighting. Studies have suggested that correctly designed daylighting systems have numerous psychological and health benefits such as: stimulation of healthy circadian rhythms, increased attentiveness and

productivity and significant reductions in stress (Boyce et al. 2003). Their usage, however, has been hampered by high prices and imperfect performance of current technologies.

Before commercialization of a product such as the daylighting system for a rural South African classroom, or any other daylighting system, can be considered, the performance of the product needs to be proven and guaranteed. The effective and efficient implementation of daylighting systems faces many challenges associated with the dynamic nature of daylight. In order to improve daylighting systems and to prove performance, it is vital to be able to take a closer look at the behaviour of the light within the illumination area. This is where the need for effective measurement of lighting metrics becomes necessary. This project therefore aims at developing a system capable of quantifying the lighting condition achieved by the daylighting system thereby allowing for further analysis of the implementation of the daylighting system.

Systems capable of recording light measurements to fit this purpose are commercially available; however, the price for such a system is extremely high. The proposed project is aimed at creating a similar system at a reduced cost.

2 Literature Review

Research conducted in the various aspects of the project is documented in the literature review. This includes investigation into the properties of light, the current technologies and methods available to measure the metrics of light and the practice of daylighting where the proposed system, for measuring light, may be utilized. The primary reason for this is to develop a thorough understanding of what the system will be required to measure and the possible means to achieve that.

2.1 What is Light

When considering the development of a system to measure and record the variability of light it is important to understand exactly what it is that will be measured. Simply put, light is a form of energy which manifests itself as electromagnetic radiation (Academy 2008). The electromagnetic spectrum is far greater than just visible light, extending from the lowest frequency radio waves through microwaves, infrared (IR), visible, ultraviolet (UV), x-rays and finally ultra-energetic gamma rays and cosmic rays as seen in Figure 1. The visible light spectrum is the only part that human eyes respond to, detecting the rest of the spectrum requires various types of scientific instrumentation (Ashdown 2002).

There exists a vast amount of literature regarding the physical aspects of light as electromagnetic radiation (Ashdown 2002). Fortunately, our interest falls primarily on how to measure that which humans can see and perceive with the human eye.

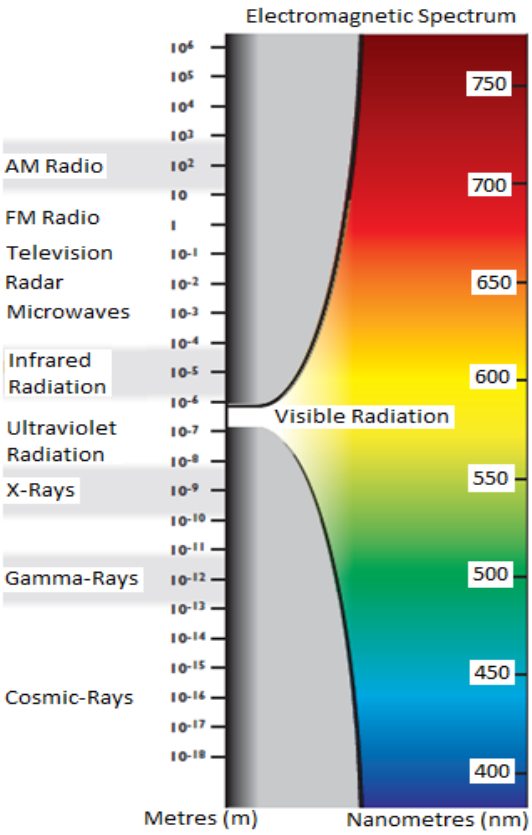

Figure 1: Optical Radiation Wavelengths of Electromagnetic Radiation Spectrum (Adapted from Academy 2008)

2.2 Daylighting

A practice, known as daylighting, is the controlled admission of natural light into a building to illuminate the interiors of dark buildings (Ander 2012). The reduction of electrical consumption utilised for interior illumination and enhanced occupant satisfaction are widely accepted benefits of daylighting (Galasiu & Reinhart 2008). This process differs from other methods of utilising solar energy for illumination as other methods utilise an energy converter to create electricity from the solar energy which powers artificial lighting, whereas daylighting utilises the natural light directly for illumination purposes (Ander 2012).

It is the implementation, advancement and improvement of systems which implement the practice of daylighting that the developed light measurement system is designed to aid.

2.3 Radiometry and Photometry

Radiation reaching the earth is primarily radiated from the Sun. The radiation from the Sun, commonly known as *Sunlight*, has been determined to be a combination of electromagnetic waves. Electromagnetic waves can range dramatically in wavelength from radio waves (10^{1} m) to gamma rays (10^{-12} m) (Villanueva 2010). Optical radiation is a term used to refer to the collective wavelength range of ultra-violet (UV) radiation through the visible range ending at the infra-red (IR) radiation wavelength, the ranges of which are shown in Figure 1.

The field of optical radiation measurement can be subdivided into two broad areas, photometry and radiometry.

Radiometry covers all techniques for the measurement of light in the electromagnetic spectrum. In the field of optical radiation measurement, radiometry is the science of measuring light in the optical radiation spectrum (Ashdown 2002).

Photometry deals more specifically with the determination and measurement of the visible, optical radiation quantities related to the perception and sensitivity of a standard human observer (Köhler 1997). Therefore, photometry focuses on the primary problem of optical measurement and quantification of lighting conditions in the visible portion of the electromagnetic spectrum between wavelengths of 390nm to 720nm (Schubert 2006).

Due to the nature of the proposed project the area of photometry will be an area of focus with little emphasis placed on the area of radiometry as a whole.

2.4 Photometric Units

Practitioners use four basic photometric units for the quantitative measurement of light (Academy 2008). These are: luminous flux, luminous intensity, illuminance and luminance, each of which is shown in Figure 2 and discussed below.

Due to the nature of the project the photometric unit of *illuminance* will be used as a means to quantify measurements and results.

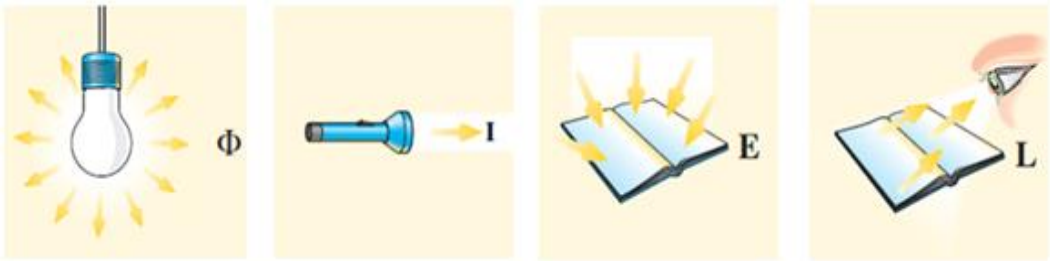

Figure 2: The Four Photometric Units: Luminous Flux, Luminous Intensity, Illuminance and Luminance (Adapted from Academy 2008).

2.4.1 Luminous Flux

Luminous flux (Φ) is the time rate of flow of light, meaning that it is the total amount of light radiated by a light source per second (Ohno 1997). The unit of luminous flux is the lumen (lm).

2.4.2 Luminous Intensity

Luminous intensity (I) is the luminous flux emitted per unit solid angle in a given direction, meaning that it is the flux of light emitted in a specific direction by a light source (Ohno 1997). The unit of luminous intensity is the candela (cd).

2.4.3 Illuminance

Illuminance (E) is the density of luminous flux incident on a point or plane, meaning that it is the amount of light falling on a unit area (Ohno 1997).

The South African Bureau of Standards (SABS) further defines a value known as the maintained illuminance, in the SANS 10114:1 document as the calculated average illuminance value on a reference plane over a period of time (SABS 2005). The unit of illuminance is lux (lx) which is lumen/m^2.

2.4.4 Luminance

Luminance (L) is the luminous flux from an element of a surface, emitted into a small solid angle containing the given direction, per unit area of the element projected on a plane perpendicular to that given direction (Ohno 1997). In other words it is the amount of light emitted from a unit area in a specific direction. Luminance is expressed as candela/m^2.

2.5 The Human Eye

Light is perceived by the human eye. In terms of the project it is therefore important to understand the functioning of the eye in order to match the measurement of light with that which would be perceived by a human observer.

The human eye, through evolution, has become a highly sophisticated and optimized sensor for electromagnetic radiation. The eye, in conjunction with the visual cortex of the brain, establishes a powerful sensory organ (Cannon 1997).

The light sensitive part of the eye is called the retina which is found cladding the interior of the eyeball. The retina contains light sensitive cells called rod cells and cone cells (Schubert 2006). Cone cells are categorized into three types according to the sensitivity of the cell to either the red, green or blue spectral range. They are known as red-sensitive, green-sensitive or blue-sensitive cones depending on which part of the spectrum they are sensitive to. Rod cells are sensitive to light over the entire visible light spectrum and are more abundant than cone cells, they are also more sensitive to light than cone cells (Schubert 2006).

Human vision is divided into three regimes depending on ambient light levels and which cells mediate the vision. Photopic vision occurs at high ambient light levels where cones mediate vision, this usually occurs at a luminance level above 3 cd/m^2 (Schubert 2006). Scotopic vision occurs at low ambient light levels where vision is mediated by rod cells, this typically occurs at a luminance level below 0.003 cd/m^2. Rods are more sensitive but the sense of colour is lost in the scotopic vision regime. Finally there is mesopic vision which occurs between the scotopic and photopic regimes where both rods and cons mediate vision in ambient light levels of between 0.003 cd/m^2 and 3 cd/m^2 (Schubert 2006). The vision regimes of the human eye are summarized in Figure 3.

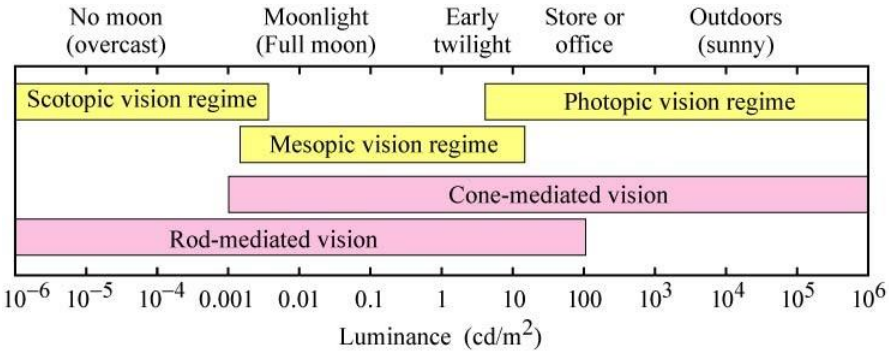

Figure 3: Human Eye Vision Regimes (Schubert 2006)

It is common in current practice for almost all photometric quantities to be given in terms of photopic vision even at low light levels (Ohno 1997). Due to this and the nature of the proposed project the regime of photopic vision will be an area of focus with little emphasis placed on the other two. The CIE[1] has defined an eye sensitivity function V(λ) for the various vision regimes as seen in Figure 4.

The sensitivity response of the human eye varies with wavelength. The photopic eye sensitivity function was first proposed in 1931 with the scotopic following in

[1] CIE Commission Internationale de l'Eclairage (International Commission on Illumination)

1951. The photopic sensitivity function has since been modified in 1978 by Judd and Vos (Schubert 2006). This modified function is the preferred function for conditions where measurements are desired that are consistent with short wavelength colour normal observers (Kaiser, 1990).

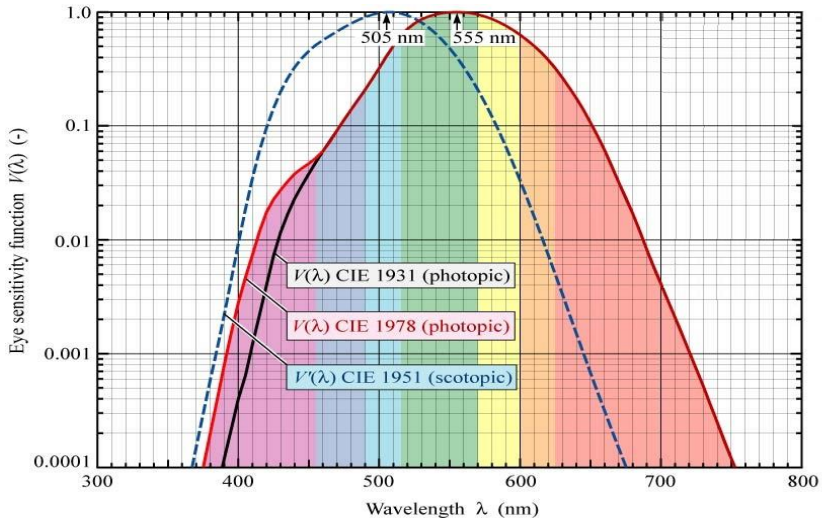

Figure 4: Eye Sensitivity Function for Various Vision Regimes (Schubert 2006)

2.6 Light Quality

Daylighting systems must ensure that lighting quality is not sacrificed in an attempt to reduce energy usage levels. It is important to meet social, safety, behavioural, aesthetic, health, emotional and immediate task needs whilst conserving resources and energy usage levels (Veitch & Newsham 1997). The maintenance of this balance is important to building occupants, building owners and other affected parties.

The lack of a common definition for lighting quality has hindered the progress of lighting systems. Veitch and Newsham attempted to address the problem by proposing a behaviourally based definition for lighting quality (Donn & Performance 2009). According to (Veitch & Newsham 1997) 'good' or 'adequate' lighting quality exists when a lighting system provides:

- Visual Performance (creates suitable conditions for seeing);
- Post-Visual Performance (sufficient illumination to perform required tasks);
- Social Interaction and Communication (promotes desirable communication and interaction);
- Mood State (generates a situationally appropriate mood);
- Health and Safety ;
- Aesthetic Judgments (provides an aesthetic appreciation of the illuminated area).

This proposition is consistent with other research focused on the relationship between working environment conditions and individual and organisational outcomes.

2.7 Quantitative Performance Metrics for Daylighting Evaluation

As mentioned in section 2.6 the concept of 'good' or 'adequate' lighting goes beyond that of mere functionality and efficiency.

2.7.1 Difficulties Associated with Daylighting Evaluation

More and more emphasis is being placed on the importance of the emotional influence of lighting, on the atmosphere providing factor, the way it affects human mood and on general health and well-being (Academy 2008).

With this in mind the performance of an implementation of daylighting is notoriously difficult to evaluate (Reinhart et al. 2006). Another difficulty in determining 'good' daylighting implementation is that different professions focus on different aspects of the daylighting practice. The architectural professions focuses on the interaction of building form and natural light to produce a productive, stimulating and healthy interior environment (Reinhart et al. 2006). Energy consultants and engineers on the other hand focus on the overall reduction of building energy requirements such as heating, cooling and lighting by intelligent control of daylighting systems (Galasiu & Reinhart 2008).

In an attempt to rate the performance of daylighting systems green building rating systems, such as LEED (Leadership in Energy and Environmental Design), express the characteristics and attributes of a daylighting system in terms of glazing factor distribution or daylight factor distribution and view-to-the-outside as quantitative performance metrics (Galasiu & Reinhart 2008).

In addition to these basic requirements such as lighting level, contrast, colour rendering, colour temperature and light distribution need to be taken into account not to mention the cost aspect involved (Academy 2008). These requirements also need to be considered and taken into account when developing a system to record the metrics of daylighting.

2.7.2 Daylighting Factor

The ratio of the interior illuminance at a point to the un-shaded, exterior horizontal illuminance under a CIE defined overcast sky expressed as a percentage is defined as the daylight factor (Reinhart et al. 2006). The concept of utilizing an illuminance ratio has been around since 1909 when the measurement technique was first published (Waldram, 1909). At the time this method proved extremely difficult due to the frequent and sometimes dramatic fluctuations in the intensity of daylight (Reinhart et al. 2006). The method was therefore modified to the current definition of the daylight factor.

Historically the daylight factor was not intended to be a performance parameter for good daylighting design but rather a means to provide legal evidence in court, based on the old Roman law of 'an absolute and indefensible rights to light' (Reinhart et al. 2006). Given this historical background, the expectation that the daylight factor can evaluate the ability of a daylighting system to provide a healthy, visually stimulating and productive environment seems fairly unfounded (Reinhart et al. 2006). Despite this the daylight factor continues to be one of the most widely utilized quantitative performance measures for daylighting practices. The most common argument for the use of the daylight factor is that the reference CIE sky is the worst case sky condition, therefore any other sky condition will result in better daylighting performance (Reinhart et al. 2006).

2.7.3 Glazing Factor

The glazing factor is similar to the daylight factor but is simply the ratio of the interior illuminance at a point to the un-shaded, exterior horizontal illuminance under a CIE defined overcast sky, whereas the daylight factor is expressed as a percentage (LEEDuser n.d.).

2.7.4 View-to-the-Outside

The LEED rating system stipulates that for a regularly occupied space at least 90% of the space should have direct line of sight to the outside. This should be through a vertical window positioned between 76 cm and 228 cm above the floor (Reinhart et al. 2006). This simple parameter was created as a view to the outside is a praised benefit of a window. This method has many shortfalls most prominently that the quality of the view influences the visual connection with the outside (Farley & Veitch, 2001).

2.7.5 Colour Rendering

Colour rendering refers to the way in which objects appear under a given light source and is measured using the Colour Rendering Index (CRI) (Academy 2008).

Light sources appearing to have the same colour, does not necessarily mean that objects will look the same under them due to different blends of wavelengths making up the light sources. Colour rendering is important for lighting applications as colours should ideally be represented as naturally as possible, the way they would be under daylight conditions.

The CRI (also denoted as Ra) scale ranges from 50-100 as described in Table 1.

Table 1: Colour Rendering Index (Academy 2008)

Colour Rendering Index Value	Colour Rendering Properties
Ra < 60	Poor
Ra = 60 – 80	Moderate
Ra = 80 – 90	Good
Ra = 90 – 100	Excellent

2.7.6 Colour Temperature

White light is a mixture of colours, however, as a result of variations in constituent colour compositions not all white colours are the same (Academy 2008). The concept of colour temperature is applied in order to classify these different whites. The colour temperature concept is described as the colour impression radiated from a perfect black body at certain temperatures (Academy 2008).

The Phillips Lighting Academy gives examples of different colour temperatures, some of which are represented in Table 2. From the table it should be noticed that daylight has a range of 5800 – 6900K depending on the sky conditions.

Table 2: Colour Temperature Examples. Adapted from (Academy 2008)

Type of Light	Colour Temperature (K)
Sunlight	5000 – 5800
Daylight (sun + clear sky)	5800 – 6500
Daylight (overcast sky)	6000 – 6900
Candles	1900 – 2500
Tungsten filament lamps	2700 – 3200
Fluorescent lamps	2700 – 6500

2.8 Dynamic Metrics for Daylighting Evaluation

As an alternative to quantitative performance metrics there exist dynamic daylight performance metrics. These methods involve the use of three-dimensional CAD software and daylight simulation models (Reinhart et al. 2006). These methods have experienced increased usage as a result of the increased availability and access to the required software.

Dynamic metric methods are based on time series of illuminance values within a building. The time series can extend over an entire calendar year allowing for the advantage over static metrics that the quantity and characteristics of variations in daylight and meteorological events are considered (Reinhart et al. 2006).

Simulation programs capable of simulating dynamic daylight applications include: Adeline, ESP-r, Daysim, SPOT, AutoDesk VIS, TracePro, Radiance and Lightswitch Wizard. The required effort to complete dynamic daylight simulations has been reduced recently allowing the use of such simulations to extend to non-expert designers (Reinhart et al. 2006).

Simulation programs utilize different analysis tools to function. The analysis tools that are used in these programs include radiosity software, forward raytracing and backward raytracing. In addition to this, simulations tools for climate analysis and sun path data are required (Rogers 2007).

Despite advances in dynamic daylight performance metrics, the proof of a system is in the physical measurement and testing of the daylighting system implementation. The proposed project will develop a system to physically measure and record data which the dynamic daylight performance metrics simulate.

The developed system can be further used to verify the results of the methods of dynamic daylight performance metrics and in turn be used to improve the methods themselves.

2.9 Types of Light Detection Systems

Types of light detection systems vary dramatically depending on the various factors such as which photometric unit is desired, which area of the spectrum is being measured and more. As a result numerous meters are available, a selection of three different meter types are discussed below to document the variations. It is clear that for the specifications of the project that an illuminance meter will be required.

2.9.1 Luminance Meters

Luminance meters are utilized to measure the photometric brightness of a surface. They are typically utilized to determine how a target appears to a specified subject. These meters are usually found in convenient ‘point and shoot’ devices (Bergin, et al., 1997).

2.9.2 Spectroradio Meters

Spectroradio meters are utilized to measure the spectra of light. This is accomplished using gratings (Bergin, et al., 1997).

2.9.3 Illuminance Meters

Illuminance meters are detectors utilized to measure the amount of flux hitting a surface. They are typically utilized for determining the ambient light level of an area. It is vital to consider appropriate placement of illuminance meters, particularly to prevent shadowing (Bergin, et al., 1997).

For the purpose of this project it is necessary to measure the ambient light within an interior space. From this it is clear that an illuminance meter is required to achieve the required system performance.

2.10 Light Detection Materials

The spectral response sensitivity band for some commonly utilized light detecting materials is shown in Figure 5. From the figure it can be clearly seen that Silicon (Si) and Gallium Arsenide Phosphide (GaAsP) have spectral sensitivity over the visible light spectrum.

Silicon photodetectors have been commonly used for many years for the detection of visible radiation. Despite this, the intensive development and improvement of silicon photodetectors can only now be noticed due to the emerging technological areas for their application (Wegrzecka & Wegrzecki 1997).

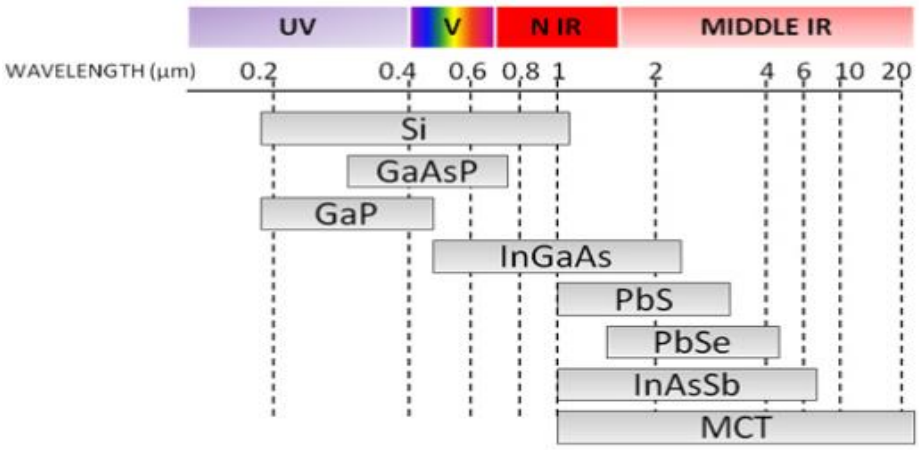

Figure 5: Various Materials Light Spectrum Sensitivity (González et al. 2012)

2.11 Classifying Light Detecting Devices

Illuminance sensors also known as photo detectors and photoelectric devices are devices which generate an output signal as an indication of the intensity of light by measuring radiant energy (Storr 2013). These devices can be grouped into two primary categories: devices which, when illuminated, generate electricity, such as photo-emissive, photo-junction and photo-voltaic devices and devices which alter their electrical properties in some way, such as photo-conductive or photo-resistor devices (Storr 2013).

2.11.1 Photo-emissive Devices

Photo-emissive devices are devices where free electrons are released from a light sensitive material, typically caesium, when a photon of sufficient energy strikes the material. The amount of energy which photons have is dependent on the frequency of the light. Higher frequency corresponds to more light energy for photons to convert into electrical energy (Storr 2013).

2.11.2 Photo-voltaic Devices

Photo-voltaic devices generate an emf proportional to the radiant light energy. The radiant light energy falls onto two semiconductor materials which are pressed together, creating a voltage typically in the range of 0.5V (Storr 2013).

2.11.3 Photo-conductive/ Photo-resistor Devices

Photo-conductive materials are materials which alter their electrical resistance when exposed to light. The effect of photoconductivity results from light striking a semiconductor material through which current flow is controlled. When incorporated as part of a circuit functioning as a resistor the device is known as a photo-resistor device or light dependent resistor (LDR). More light increases the current for a specified applied voltage. The most common photoconductive material utilized in LDR devices is Cadmium Sulphide (Storr 2013).

2.11.4 Photo-junction Devices

Photo-junction devices are devices which use light to control the flow of electrons and holes across their PN-junction. The devices are true semiconductor devices such as photodiodes. Photo-junction devices are specifically designed for applications with spectral response tuned to the wavelength of incident light (Storr 2013).

Due to the nature of photo-junction devices they will be the primary focus of the project as a means to measure the illuminance values, specifically devices that are designed for spectral responses similar to that of the human eye.

2.12 Light Detector Examples

An instrument utilized for measuring the amount of light is called a photometer (Cannon 1997). A complete list of photometers is extensive; this section therefore limits the discussion to sensors which can be utilized in illuminance measurement applications. This section expands upon some examples of photometers which fall into the categories of the light detecting devices classified in section 2.11.

2.12.1 Photodiodes

Photodiodes are semiconductor, light sensitive devices. They are essentially manufactured in the same manner as semiconductor diodes that are utilized in conventional electronic circuits (Godfrey 1997).

Silicon based photodiodes are capable of covering the wide range of wavelengths from 190 to 1100 nm (Godfrey 1997). These p-i-n photodiodes are typically used for detection in the visible spectrum (Bergin, et al., 1997).

Germanium (Ge) photodiodes overlap the response spectrum of silicon and are usable for detection near and in the UV range up to about 1600 nm (Bergin, et al., 1997).

Semiconductors which are compounds of arsenide, gallium, antimonide, indium and phosphorous can be specifically fabricated to detect specific sections of the 190 to 2000 nm spectral range. It is possible to fabricate more specific and expensive photodiodes can sense energy much further out in the IR spectrum (Godfrey 1997).

The quality of silicon photodiodes has improved significantly resulting in widely available high quality silicon photodiodes (Ohno 1997). This marks a significant improvement in the quality of commercial photometers and illuminance meters with their use becoming more widespread including: ambient light sensing, ambient backlight control, contrast control, camera light meters, lighting control systems, HVAC systems, home appliances, office automation equipment and much more.

2.12.2 Photoresistors

Photoresistors have been developed since the discovery of photoconductivity in selenium was made by Willoughby Smith in 1873 (Poole n.d.).

Many variations of photoconductive devices have been made since Smith's discovery. Work was done by T.W. Case in the early 1900's on the use of Thalofide (a combination of thallium, oxygen and sulphur). Other substances investigated included Lead(II) sulphide (PbS), Lead selenide (PbSe) and Lead telluride (PbTe) in the 1930's and 1940's. Finally in 1952 photoconductors using silicon and germanium were developed by Rollin and Simmons (Poole n.d.).

2.12.3 Photovoltaics

Most photovoltaic cells are constructed from single crystal silicon PN junctions, the same as photodiodes but are used without the reverse bias, with a very large light sensitive region. Silicon used in these devices can be monocrystalline, polycrystalline or amorphous (Storr 2013).

The most common type of photovoltaic sensor is the Solar Cell which is capable of converting light energy directly into DC electrical energy (Storr 2013).

Other materials utilized in the manufacture of photovoltaic cells include Cadmium Telluride, Copper Indium Diselenide and Gallium Arsenide. These materials each have a different sensitivity spectrum band response, and so can be specifically utilized to produce an output voltage at different light wavelengths (Storr 2013).

2.12.4 Photomultiplier Tubes (PMT)

Photomultiplier tubes (PMT) are vacuum tubes capable of converting photons into electrons by utilizing the photoelectric effect (González et al. 2012). The tubes utilize a light sensitive surface, known as the photocathode that absorbs photons and emits electrons.

The emitted electrons accelerate and are multiplied by dynode plates within the tube. When an electron strikes a dynode it has enough energy to create additional electrons (Godfrey 1997). A tube with just 10 to 12 dynodes is capable of multiplications of over a million, generating sufficient current to develop hundreds of millivolts over a 50 ohm output resistor for just a single photon.

These tubes are the ultimate in light detection sensitivity (Godfrey 1997).

Many materials can be utilized in photomultiplier tubes, some of these are listed below.

- Ag-O-Cs: which is sensitive from 300–1200 nm and is used mainly in near-infrared region with the photocathode cooled.
- GaAs:Cs: caesium-activated gallium arsenide which has a flat response from 300 to 850 nm, fading towards ultraviolet and to 930 nm.
- InGaAs:Cs: caesium-activated indium gallium arsenide has a higher infrared sensitivity than GaAs:Cs.
- Sb-Cs: caesium-activated antimony is used in reflective mode photocathodes. The sensitivity range is from ultraviolet to visible.
- Multialkali (Na-K-Sb-Cs): wide spectral response from ultraviolet to near-infrared; special cathode processing can extend range to 930 nm with use in broadband spectrophotometers.
- Solar-blind (Cs-Te, Cs-I): sensitive to vacuum-UV and ultraviolet. Insensitive to visible light and infrared (CsTe has cutoff at 320 nm, CsI at 200 nm).

2.12.5 Phototransistors and Photodarlingtons

Phototransistors are transistors that are designed to capture light. These devices can occasionally be more convenient than photodiodes as they have a built in gain. Current created at the base region of the phototransistor by absorbed light results in gains of 100 to several thousand (Godfrey 1997).

Photodarlingtons are phototransistors with a second gain stage. This results in gains of up to 100 000 (Godfrey 1997).

The more modern phototransistors use type III-V materials such as gallium arsenide.

2.13 Interior Illumination Levels

A Code for Interior Lighting produced by the South African Bureau of Standards provides recommendations and basic guidelines for interior lighting (SABS 2005). This code is the ‘SANS 10114-1:2005 Edition 3 Interior lighting Part 1: Artificial lighting of interiors’ published by SABS Standards Division.

The code establishes a table of minimum allowed, maintained illuminance values for numerous areas of illumination. Table 3 has been adapted from the SABS, SANS 10114-1:2005 document and shows the lighting requirements for some

general building areas. Examination of the code for interior lighting, as well as Table 3, shows that for general areas the required illumination values range from 100 lux to 500 lux depending on the interior area, task or activity with colour rendering values of over 40.

In the table, Column 1 documents the specific interior to which the lighting requirements apply. Column 2 shows the minimum maintained illuminance E_m value allowed in lux. Column 3 shows the maximum unified glare rating (UGR). Column 4 gives the minimum colour rendering indices (R_a) and finally column 5 gives some general remarks.

Table 3: Minimum Maintained Illuminance Values

1	2	3	4	5
Type of interior, area, task or activity	**E_m, Min. (lux)**	**UGR, max.**	**R_a, min.**	**Remarks**
General Building Areas				
Entrance halls	100	22	60	
Lounges	200	22	80	
Circulation areas and corridors	100	28	40	
Stairs, escalators, travelators	150	25	40	
Loading ramps/bays	150	25	40	
Canteens	200	22	80	
Rest rooms	100	22	80	
Rooms for physical exercise	300	22	80	
Cloakrooms, washrooms, bathrooms, toilets	200	25	80	
Sick bays	500	19	80	
Rooms for medical attention	500	16	90	
Plant rooms, switch gear rooms	200	25	60	
Post rooms, switchboards	500	19	80	
Stores, stockrooms, cold stores	100	25	60	200 lx if continuously occupied
Dispatch packing and handling areas	300	25	60	
Control stations	150	22	60	200 lx if continuously occupied

3 DESIGN REQUIREMENTS

The design requirements form the foundation of the design process. These requirements form the criteria with which to evaluate the system and determine the suitability of the system to perform the desired application. The design requirements identified for the project are outlined in this section.

- Measure ambient light level, in the visible spectrum, as seen by the human eye.
- Measure ambient light level in the range of 100 lux to 1000 lux to completely cover the range of recommendations and basic guidelines for interior lighting of general areas.
- Measurements must be within an accuracy range of ±10%.
- System capable of measuring the ambient light level of an area 2 m x 2 m in size on a horizontal plane.
- Light measurements must result in a resolution of no more than 0.5 m x 0.5 m within the area (therefore a minimum of 4 illuminance sensors are required in a 1 m x 1 m area).
- Record data measurements simultaneously for the specified area at predefined time intervals.
- Efficient data extracting and processing for analysis and visualisation.
- Simple sensor replacement in the event of a failure or malfunction.
- Cost in the range of an order of magnitude less than commercially available systems.
- System should be portable.
- All system components should be locally available.
- All system components must be non-toxic.

4 CONCEPTUAL DESIGN

When developing a concept system design various factors need to be taken into account while still meeting the design requirements of the system. This section documents the iterative process of analysis, synthesis and evaluation involved in the process of creating a system concept.

4.1 Conceptual Design Overview

The final system must meet the requirements laid out in section 3, however, before this stage can be reached concept development as well as sensor testing and selection are required. For the concept development and sensor testing aspect of the project a microcontroller system will be required. Simply put, the system must receive a signal from an illuminance sensor being tested for consideration in the final system design, convert that signal using the analogue to digital convertor and display the result on the LCD screen for quick and easy viewing. A simplified version of the system is shown in Figure 6.

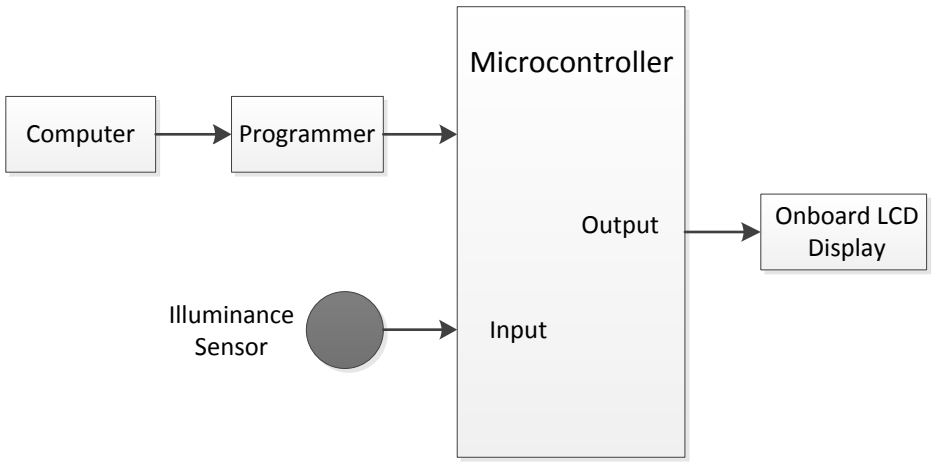

Figure 6: Simple Microcontroller Based Illuminance Sensing System used for Testing Concept Sensors

This shows a very simple depiction of what the system will be like during concept development and sensor testing, however it must be kept in mind that the prototype system will be far more complicated and precautious must be taken when considering the concept so that the integrity of the final prototype design is not jeopardized.

4.2 Conceptual Design Layout

Three possible design layouts identified for the final system are detailed. A number of the more influential design factors and requirements are then discussed in relation to each concept. In the discussions regarding the various layouts it is assumed that ideal illuminance sensors are available for use in the system.

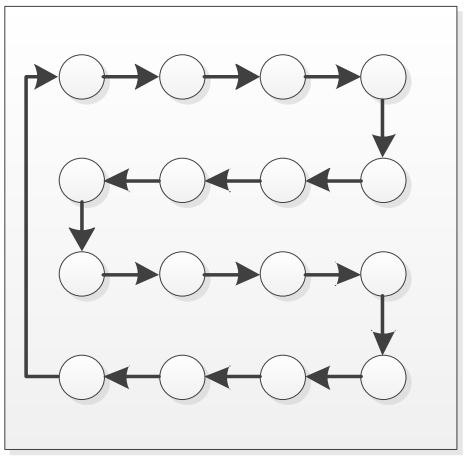

Figure 9: Single Sensor in Motion Concept

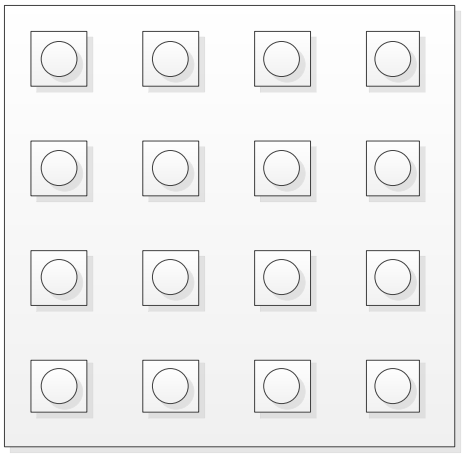

Figure 8: Multiple Node Concept

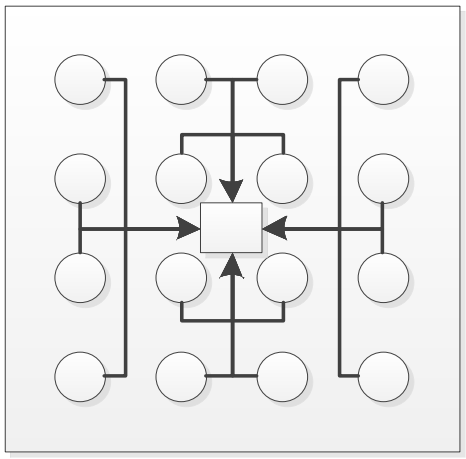

Figure 7: Central Node Multiple Sensor Concept

4.2.1 Single Sensor in Motion Concept Design

The single sensor in motion concept was identified in an attempt to simplify the system and minimise materials and components required for the system.

The concept proposes the use of a single sensor which moves around the area in which measurements are to be taken, taking the required data measurements at predefined locations. Essentially the sensor will stop at a specified location, measure and record data and then move to the next location. A representation of a single sensor in motion system is shown in Figure 9.

With a system such as this it will be possible to specify many measurement locations meeting the resolution and required area sizes, however, simultaneous measurement will be impossible. Large delays will occur between taking the first and last measurements which could lead to an inaccurate representation of the results. The movement component of the design introduces more potential for malfunction or failure of the system.

The cost of such a system is expected to be very low as component numbers are minimised. Sensor replacement will be simple and the system would have high portability and customisability.

4.2.2 Multiple Node Concept Design

The multiple node concept was identified in an attempt to highlight customisability of the system.

Essentially the system comprises multiple identical nodes which are self-contained. Each node would have the capability of measuring and storing data the way the single sensor design did. However without the movement component the design will be more reliable with less risk of failure. The system size could be increased or decreased by simply adding more or removing nodes. The data from each node would have to be added to the other nodes in order to generate the system characteristics which could prove time consuming. A representation of a multiple node system is shown in Figure 8.

The use of a system such as this will meet the resolution and size requirements easily with a high degree of customisability available, as well as allowing for multiple, simultaneous measurements and data recording.

The cost of such a system is anticipated to be fairly high due to the high number of components. Sensor replacement will be simple and the system would have good portability.

4.2.3 Central Node Multiple Sensor Concept Design

The central node multiple sensor concept was identified in an effort to minimise system components while maintaining a high level of customisability.

The system comprises a central node connected to multiple sensing units. The central node is responsible for all system interfacing, sensor control and data aggregation. The sensing units are simply sensors which relay their signals to the central node. This concept can be visualised as an octopus with the central node being the head and each sensor being a tentacle. A representation of a central node multiple sensor system is shown in Figure 7.

The use of a system such as this will meet the resolution and size requirements. There will be some limitations on the customisability of the system due to the physical connections between the central node and the sensing units. Multiple, simultaneous measurements and data recording will be possible.

The cost of such a system is anticipated to be fairly high due to the high number of components. Sensor replacement will be simple and the system would have fair portability.

4.3 Concept Layout Comparison and Selection

In order to assess the validity and viability of a concept layout it must be known how well it will meet the design requirements. Table 4 shows a comparison between the three identified concept layouts and how well they meet some of the design requirements.

In the table a tick (√) indicates that the concept meets the requirement well, a circle (O) indicates that the concept meets the requirement to some extent and a cross (X) indicates that the concept does not meet the requirement well.

From Table 4 it can be seen that all three concepts meet most of the design requirements. However, both the single sensor in motion and the multiple node concepts fail to meet one or more requirements. The fact that the single sensor design is not able to take simultaneous measurements at various locations is seen as a major drawback and an immediate disqualifying factor, while the cost factor of having multiple nodes and potential complications with data processing are the primary reasons for the exclusion of the multiple node design.

Table 4: Comparison of Concept Layouts

Design Requirement	Single Sensor	Multiple Node	Central Node
Multiple location measurement	√	√	√
Resolution	√	√	√
Measurement area	√	√	√
Simultaneous measurement	X	√	√
Efficient data extracting and processing	√	X	√
Simple sensor replacement	√	√	√
Cost	√	X	O
Portability	√	√	O

The central node concept meets most of the requirements well with the exception of cost due to the need for multiple of sensors and portability as the cables required to link each sensor to the central node could prove cumbersome. However it was felt that the design positives outweighed the negatives and was therefore selected as the layout to be used in the concept design. Every effort will be made to minimise the cost factor of the design and maintain high levels of portability.

4.4 Hardware Selection

As discussed in section 4.3 a central node concept design was selected for the layout of the system. This section will develop this layout further by outlining the selection of hardware required for initial sensor and system testing.

4.4.1 Central Node

The central node for the central node concept is responsible for all system interfacing, sensor control and data aggregation. A microcontroller system is required to perform these functions and it is therefore vitally important that the selection of this hardware be critically investigated.

From several various possibilities the project focused on a system design using the programmable interface controller (PIC) series of microcontrollers manufactured by Microchip Technology Inc.

The PIC18 series of microcontrollers are advanced, high performance devices developed for high-pin-count, high density and complex applications and can be utilized in cost effective solutions for applications written in C (Ibrahim 2010).

From this series the PICDEM™ PIC18F8722 Explorer Demonstration Board was selected to be the central node. The board is controlled by a PIC18F8722 microcontroller mounted on the board. This decision was very difficult to make due to the wide variety of possibilities. However, the PIC18F8722 Explorer Demonstration Board (referred to as the devboard in the project), which can be seen in Figure 10, stood out with many advantages to selecting this device:

- Microchip's PIC series is widely utilised in industry today. The series has proven to be reliable, efficient, effective and good value.
- The demonstration boards are ideally suited to prototype development.
- The use of such a board eliminates the need to design a PCB saving a lot of time.
- The PIC18 has a high number of IO pins with 80 pins all of which have easy access points. This allows for numerous connections when interfacing with multiple sensing units.
- The on board LED's can be utilised for debugging purposes.
- The on board LCD display can be useful to display outputs visually when calibrating and testing sensor units.

- The PIC18 has I^2C capability with multiple channels to accommodate a large number of sensors as the sensors could be hardwired with the same ID.
- A real time clock module for time stamping during data recording is present on the PIC18.
- RS232 communication is possible for communication between the MCU and a PC. It is also possible to convert RS232 communications to USB protocol.
- AD convertor with multiple channels available for analogue sensors.
- Accommodates and is compatible with numerous PICtail daughter boards such as the SD card module.
- Has both 3.3V and 5V supply capabilities.
- Can be programmed with the free MPLAB IDE software development tool.
- Is compatible with Microchip's MPLAB C18 C compiler for the PIC18 MCU fully integrated with MPLAB IDE.
- Expansion capabilities such as connecting to a GPRS modem to upload data to a server and display it through a web portal.

Figure 10: PIC18F8722 Explorer Demonstration Board (Adapted from (Microchip 2008)**)**

4.4.2 Illuminanace Sensor Unit Identification

When selecting a detector for a light detecting application the choices can be overwhelming. It has already been concluded that an illuminance sensing device is required to meet the requirements of the system. There are many options available including: photodiodes, phototransistors, photoresistors, photomultiplier tubes, photodarlingtons, integrated circuits and others as discussed in section 2.12.

For each application, specific needs of the application need to be considered, these include:

- Light source spectral characteristics
- Mating electronics
- Packaging constraints
- Cost
- Frequency bandwidth

In addition to the application requirements it is important to consider the general characteristics of each prospective sensing device. The general characteristics to be considered include:

- Lifespan
- Cost
- Spectral response
- Sensitivity
- Accuracy
- Performance relative to cost
- Durability
- Size
- Ease of customization
- Local availability
- Toxicity
- Output type (analogue or digital)
- Output response curve
- Mounting type (surface mount, through-hole)
- Component type (photodiode, photoresistor etc.)

Technological advancements in the field of high quality silicon photodiodes discussed in section 2.12.1 led to the decision to focus on this specific type of illuminance detector devices.

In order to find the most appropriate sensor for the purpose of the project it was decided to investigate several different sensing components with a varying range of general characteristics. A summary of the components selected for consideration is shown in Table 12 in appendix F.1.

The number of devices summarized in the table was further reduced before concept sensor development occurred.

The APDS-9005-020, GA1A2S100LY, and SFH 5711 were selected for further investigation and evaluation. Should these prove unsatisfactory for the project objectives, testing of the other potential sensor devices will occur.

The limited range of the GL5528 photoresistor lead to its exclusion as a maximum range of 100 lux is unacceptable. The two APDS and the two SFH sensors were then considered and one of each was selected. The SFH5711 to examine the effect

of a logarithmic output and the APDS-9005-020 to avoid the unnecessary complications involved with reverse mount surface components.

4.4.3 Temperature Sensor Unit Identification

Temperature measurement is not the prime focus of the project but is required to determine temperature fluctuations within the calibration environment. A simple Low-Power Linear Active Thermistor will achieve the desired results.

The MCP9700A-E/T0 manufactured by microchip was selected for use in the project. An extract of the front page of the datasheet for this device may be seen in appendix A.5. This particular sensor is an analogue temperature sensor with a temperature range of -40°C to 125°C with an accuracy of ±2 ^{o}C between 0 ^{o}C and 70 ^{o}C. This accuracy can be improved to ±1 ^{o}C with correct calibration. The MCP9700A is optimized for analogue-to-digital conversions with an output reference of 10.0mV/^{o}C.

The simple temperature sensor circuits were tested and found to be in acceptable working condition.

4.5 Software Selection

When working with and programming devices such as those in the PIC18 series of microcontrollers, there are numerous C compilers that can be used (Ibrahim 2010). These compilers can all be utilised to develop high-level C-based programs for the PIC18 series of microcontrollers as the features of the compilers are mostly similar (Ibrahim 2010).

Some of the more popular C compilers used for the PIC18 microcontrollers, used in the development of commercial, educational and industrial applications include (Ibrahim 2010):

- mikroC C compiler (developed by *MikroElektronika*)
- PICC18 C compiler (developed by *Hi-Tech Software*)
- CCS C compiler (developed by *Custom Computer Systems Inc.*)
- MPLAB C18 C compiler (developed by *Microchip Inc.*)

The choice of compiler is fairly arbitrary, so to keep with consistency the Microchip developed MPLAB C18 C compiler (or C18 compiler) is used for this project. Available from the Microchip Website is an evaluation version (student version) of the compiler, free of charge. This includes a large set of library functions which aid program development.

The C18 compiler is a cross compiler where programs are developed on a PC before being loaded onto the memory of the microcontroller using a suitable programming device (Ibrahim 2010). The PICkit 3 Programmer/Debugger is used to load the programs onto the PIC18F8722 microcontroller mounted on the

demonstration board. This device is a simple, low cost, in circuit debugger controlled by a PC running an MPLAB IDE on a windows platform.

The MPLAB IDE (integrated development environment) software must be installed before installing and using the C18 compiler (Ibrahim 2010).

4.6 Method for Sensor Testing

The sensors selected for consideration in the final system design will be tested to determine their effectiveness, accuracy and suitability for use in the final system design. The method developed for testing and evaluating the sensors is documented in this section.

4.6.1 NIST Calibration Set-Up

Calibrated standards of luminous intensity, illuminance and colour temperature are supplied by the National Institute of Standards and Technology (NIST) (Ohno 1997). The photometry bench set-up used for the calibration procedure for luminous intensity and illuminance calibrations, documented by (Ohno 1997) is shown in Figure 11.

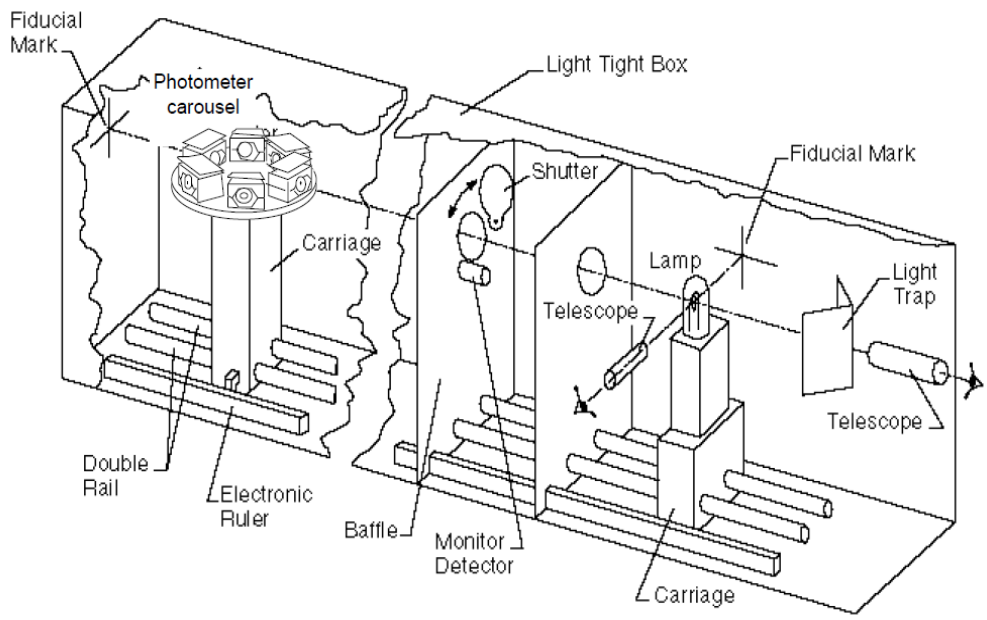

Figure 11: NIST Photometry Bench Set-Up

4.6.2 Illuminance Sensor Testing Set-Up

The procedure, equipment and techniques used to perform calibrations by NIST were examined and adjusted slightly to suit the requirements of the project and facilitate testing of the concept sensors.

The test chamber was changed to a vertical design with a downward facing lamp situated at the top of the test chamber and the sensor situated on the bottom level. Two baffles limit the amount of light passing through to the sensor as well as ensuring that the light hitting the sensor is consistent and uniform. The intensity of the light striking the sensor is altered by altering the intensity of the lamp.

The sensor chamber is light tight with all interior surfaces painted matte black in order to minimize reflection and ambient light interference. A simplified design for the testing chamber can be seen in Figure 12.

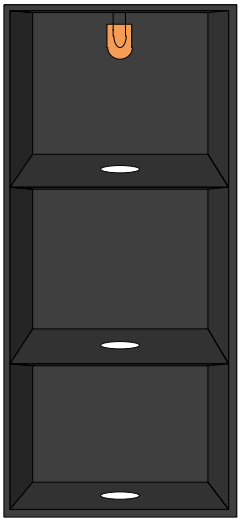

Figure 12: Testing Chamber Set Up

4.6.3 Lamp Selection

The selection of the lamp to be used within the testing chamber is extremely important. If the testing and resulting calibrations are not suited to a light source similar to the one that the system will measure, then inaccuracies may occur.

To minimize these inaccuracies the test lamp will be chosen to have similar characteristics to that of natural daylight, as the desired system use is for the monitoring and improvement of daylighting systems. As a result we are looking for a lamp that has a high CRI value (preferably 80 or higher) with a colour temperature in the range of daylight (5800 – 6900K) as described in sections 2.7.5 and 2.7.6 respectively.

Table 5 gives an overview of some typical light source characteristics for common light sources. From the table it can be seen that an LED lamp is most likely to have the required high CRI value and correct colour temperature value with other light sources failing in one or both of the criteria.

White light generation with LEDs is tricky as by nature they can only generate monochromatic colours. However, colour mixing can be used to achieve a white

light but this can lead to a discontinuous colour spectrum. The more current approach is to cover blue LEDs with phosphor coatings that have the ability to convert part of the blue light to other colours resulting in a white with CRI values above 80 which are classified as good to excellent (Academy 2008).

An Osram *LED SUPERSTAR PAR 16 50 36° ADVANCED 7.5W* lamp was selected as a test lamp for the testing procedure. An extract from the datasheet for this lamp can be seen in appendix A.4. The lamp is fully dimmable which allows for light intensity adjustments during testing. The lamp has a colour temperature of 6500K suiting the daylight colour temperature criteria, while also having a CRI value of 80.

Table 5: Overview of Typical Light Source Characteristics. Adapted from (Academy, 2008)

Lamp Type	Luminous flux (lm)	Power (W)	Efficiency (lm/W)	Colour Rendering Index (R_a)	Colour Temperature (K)
Incandescent/halogen	60 - 48400	5 - 2000	5 - 27	100	2700 - 3200
Low-pressure sodium	1800 - 32500	18 - 180	100 - 203		1700
High-pressure sodium	1300 - 90000	35 - 1000	50 - 130	10 - 80	2000, 2200, 2500
High-pressure mercury	1700 - 59000	50 - 1000	35 - 60	40 - 60	3400, 4000, 4200
Fluorescent	200 - 8000	5 - 80	60 - 105	60 - 95	2700, 3000, 4000, 6500
Compact fluorescent	200 - 12000	5 - 165	50 - 85	80	2700, 3000, 4000, 6500
Metal halide	5300 - 220000	70 - 2000	75 - 140	65 - 95	3000, 4000, 5600
Ceramic metal halide	1500 - 23000	20, 35, 70,150, 250	68 - 95	80 - 95	3000 - 4200
LED	10 - 170	0,1 - 3W	Up to 50	up to 90	3000 - 8000

4.6.4 Light Control Circuit

In order to control the conditions of illumination within the testing setup a trailing edge dimmer module (SDIM-T-LED-500W) manufactured by Shuttle with the data sheet shown in appendix A.2 is utilized.

This range of dimmers, manufactured by Shuttle, is recommended by Osram for use with their lamps (Shuttle 2013). The dimmer module is SANS and SABS approved as seen on the data sheet and meets the requirements of the project allowing for the intensity of the LED lamp to be controlled and the level of illumination within the testing setup to be adjusted.

4.6.5 Testing Procedure

In order to determine the effectiveness of the concept sensors, the results obtained by each concept sensor under controlled conditions will be compared to data recorded by an industry standard SDL400 Light Meter from Extech Instruments the data sheet of which can be seen in appendix A.3.

This method of testing was considered acceptable as significant improvement in the quality of photometers utilizing silicon photodiodes has resulted in many commercially available photometers being able to be used as standards instead of traditional luminous intensity standard lamps (Ohno 1997).

Some of the notable features and characteristics of the SDL400 include:

- Range 0 – 100 klux
- Resolution 1 lux
- Accuracy +-4%
- Precision silicon photo diode
- Datalogger with date/time stamp capabilities
- Adjustable data sampling rate

The SDL400 device is shipped fully tested and calibrated (User Guide 2014).

The procedure to be followed when testing the sensors will be to set the lamp intensity, measure the resulting lux value with the industry standard sensor and then take a measurement with the concept sensor(s). The intensity of the lamp is altered to give illuminance levels ranging from of 100 lux to 2000 lux.

Before testing can begin the lamp needs to be 'seasoned'. The NIST procedure requires a 48hr, full power seasoning time followed by a 72hr, 85% power seasoning period to allow for aging characteristics to stabilize (Ohno 1997).

Due to the lower power requirements of LED lamps it is expected that the temperature of the interior of the test chamber will not be significantly altered by the presence of the lamp. This was confirmed by multiple tests, allowing the lamp to shine at full intensity for a period of 3 hours. During this time period the temperature rose, on average, from 22.825 $^{\circ}$C to 23.313 $^{\circ}$C within the test chamber.

This slight change in temperature is assumed to be negligible as the ambient temperature of the room over the period of a day will have more of an effect on the interior of the test chamber than the lamp. Once it was determined that temperature increases by this lamp type would not cause any risks a new lamp was seasoned in the manner described by NIST procedures.

Care is taken to clean the lamp with a soft, lint-free cloth to remove any dust accumulation and direct contact with bare hands is avoided.

Care must also be taken to allow the lamp to stabilize. To ensure this the lamp intensity is set and allowed to stabilize at maximum and again at minimum intensity with recordings taken at regular intervals documenting the stabilization of the illuminance value. The resulting lamp stabilization curves are as shown in Figure 13 and Figure 14.

From the figures it can be seen that the lamp stabilizes to within 5% of its final value within 27 minutes at maximum intensity and within 15 minutes at minimum intensity. The exact value is reached after 37 minutes and 17 minutes respectively. Therefore, in order to ensure that the lamp has stabilized, a period of 40 minutes will be waited between setting the lamp intensity and recording the first measurement.

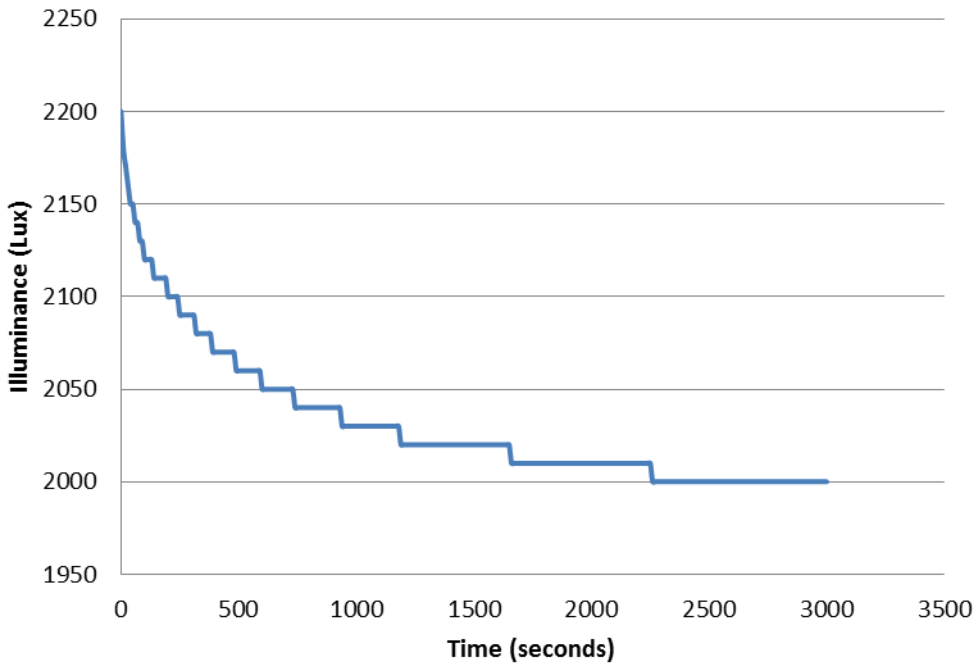

Figure 13: Test Lamp Stabilisation Curve for Maximum Intensity

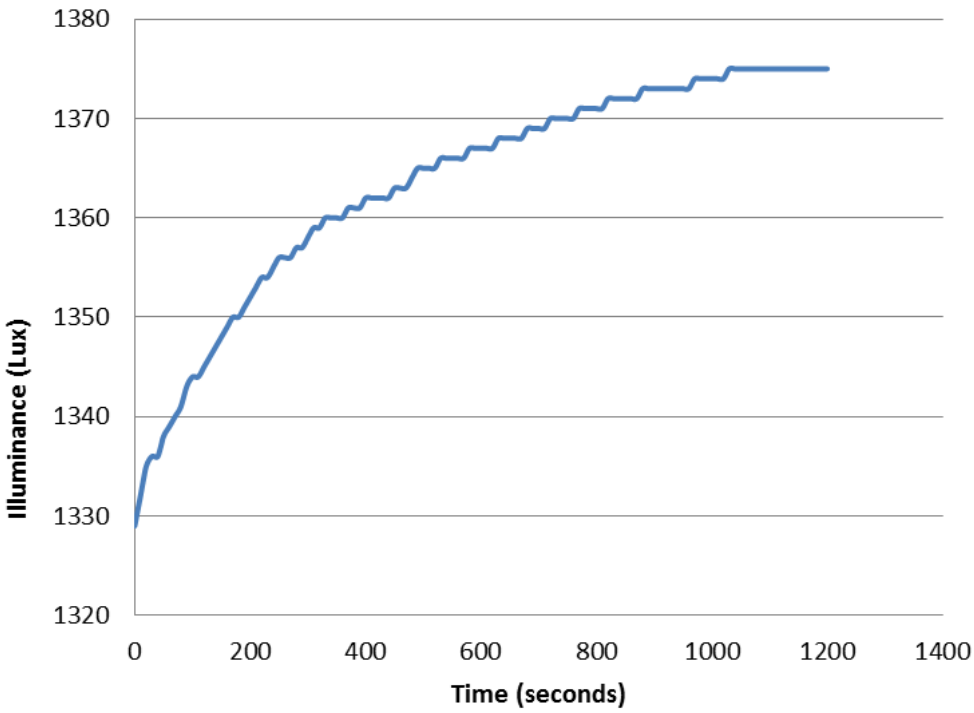

Figure 14: Test Lamp Stabilisation Curve for Minimum Intensity

5 ILLUMINANCE SENSOR DEVELOPMENT

This section documents the development, testing and evaluation of the APDS-9005-020, GA1A2S100LY, and SFH 5711 potential sensor designs. The selection of these three sensors as potential sensors in the system is documented in section 4.4.2.

5.1 Sensor Design

Extracts from the data sheets for each sensor, chosen for further evaluation, can be seen in appendix A.1. In order for further evaluation to occur the sensor circuits need to be designed and constructed for testing purposes.

5.1.1 Sensor Mounting

The primary characteristic to consider when designing and developing the sensor circuits is the mounting of the sensor. For through-hole components a simple testing circuit can be constructed using Vero-Board which is ideal for concept prototyping. However, for surface mount components a footprint board will need to be designed and manufactured onto which the surface mount component can be mounted.

From the selected sensors only the Sharp GA1A2S100LY is through-hole. This sensor circuit will therefore be simply constructed using Vero-board. Printed circuit board (PCB) designs will be made for the remaining sensor types using Altium Designer Software.

5.1.2 Sharp GA1A2S100LY

The following values for the recommended operating conditions required for the design of the circuit were obtained from the device data sheet.

Supply Voltage:	V_{CC} = 2.7 to 3.6V
Supply Current:	I_{CC} = 325 to 675µA
Output Voltage:	V_{OUT} = 0 to (V_{CC} – 1) V
Illuminance Range:	E_V = 10 to 10000 lx
Operating Temperature:	T_{opr} = 0 to 70°C
Load Resistor:	R_L = 1kΩ

A 0.1uF bypass capacitor C_{filter} is connected between V_{CC} and ground with a load resistor R_{Load} between the output and ground. The capacitor is implemented as a 'smoothing' capacitor to limit the interference of noise on that sensor output signal. Figure 15 shows the resulting circuit diagram for the sensing device and Figure 16 shows an example of the prototype sensor.

A total of four Sharp GA1A2S100LY sensor circuits were developed for testing purposes.

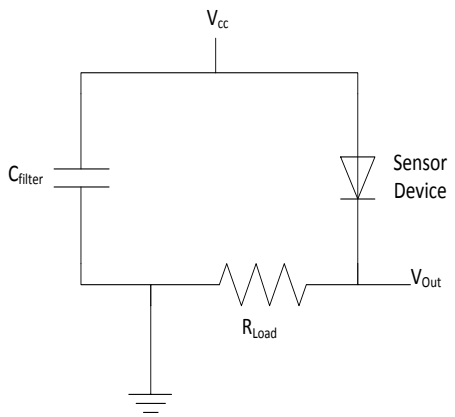

Figure 15: Typical Sensor Circuit Diagram

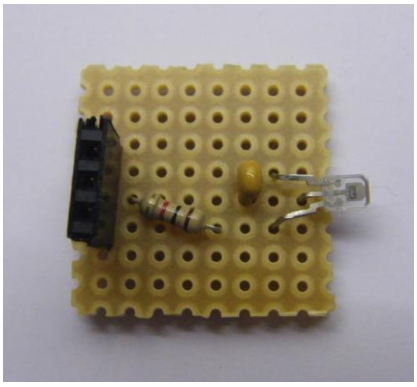

Figure 16: Sharp Sensor Testing Prototype

5.1.3 APDS-9005-020

The following values for the recommended operating conditions required for the design of the circuit were obtained from the device data sheets.

Supply Voltage:	V_{CC} = 1.8 to 5.5V
Illuminance Range:	E_V = 10 to 1000 lx
Load Resistor:	R_L = 1kΩ
Operating Temperature:	T_{opr} = -40 to 85°C

A 0.1uF bypass capacitor C_{filter} is connected between V_{CC} and ground with a load resistor R_{Load} between the output and ground in the same manner as previously. The basic circuit is the same as shown in Figure 15. Figure 17 shows a complete sensor used for testing with the prototype footprint with sensor attached, mounted on Vero with the load resistor and filter capacitor.

A total of four APDS-9005-020 sensor circuits were developed for testing however one of the developed circuits failed to operate correctly.

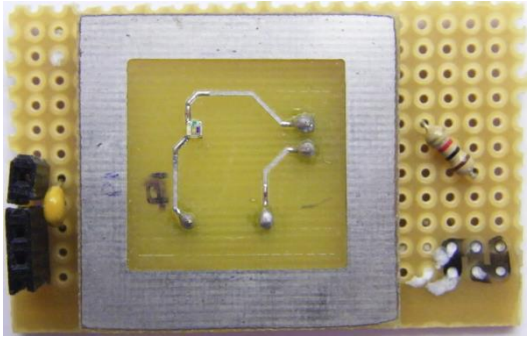

Figure 17: APDS Sensor Testing Prototype

5.1.4 SFH 5711

The following values for the recommended operating conditions required for the design of the circuit were obtained from the device data sheets.

Supply Voltage:	V_{CC} = 2.3 to 5.5V
Supply Current:	I_{CC} = 550µA Maximum at 1000 lx
Illuminance Range:	E_V = 3 to 80000 lx
Operating Temperature:	T_{opr} = -30 to 70°C
Output Voltage:	V_{OUT} = 0 to (V_{CC} – 0.5) V
Transfer Function:	$I_{out} = S*\log(E_V/E_O)$:where E_O = 1 lx : and S = 10 µA

As previously, a 0.1uF bypass capacitor C_{filter} is connected between V_{CC} and ground with a load resistor R_{Load} between the output and ground as shown in Figure 15. Figure 18 shows an example of the completed prototype footprint with sensor attached, mounted on Vero with the load resistor and filter capacitor used for sensor testing.

A total of three SFH 5711 sensor circuits were developed for testing. Unlike with the other sensor circuits the three are not identical, the third sensor has a different load resistance to investigate the influence this will have on measurements.

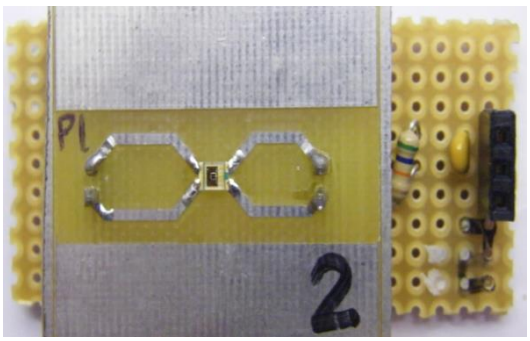

Figure 18: SFH Sensor Testing Prototype

5.2 C Software Development for Sensor Testing Main

As mentioned previously in section 4.4 the development board used for the project is controlled by a PIC18F8722 microcontroller mounted on the board. Also stated previously was the need for an integrated development environment and compiler, selected to be MPLAB X IDE and the MPLAB C18 C respectively, for the development of the project.

In order to facilitate sensor testing the main method outlined in Figure 19 needs to be developed using the selected software. An example of the C code developed to perform these operations is shown in appendix B.1.

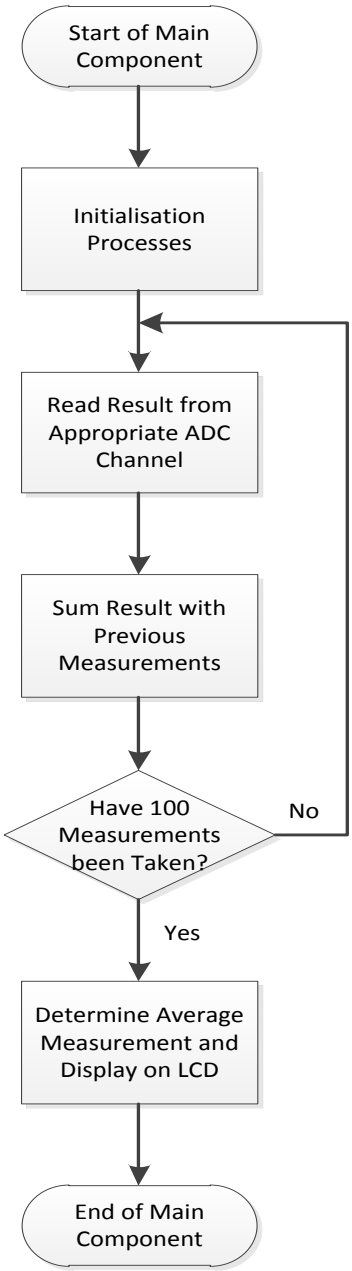

Figure 19: Main Method for Concept Development

The initialization processes mentioned in Figure 19 refers to actions such as initializing variables, configuring the required LCD parameters, Analog-to-Digital Converter (ADC) parameters and certain input/output pins so that they can be utilized effectively later in the program.

Sensor outputs will be received by the PIC18 devboard through configured input/output pins where they will be read and converted by the ADC. The resolution of the ADC situated on the devboard is 10 bits which is adequate for the requirements of the project.

An average value of 100 successive sensor measurements is determined in an attempt to reduce any potential sensor errors or light fluctuations. The result from this is displayed on the on-board LCD screen for quick view and data recording purposes.

5.3 Results

Each of the sensors developed for testing is tested using the procedure laid out in section 4.6. The results from the industry standard sensor as well as the test sensors are recorded in a Microsoft Excel spreadsheet. An extract of such a spreadsheet, showing the raw output values of the various sharp sensor devices, is shown in appendix D.1.

Results are recorded as raw data before being processed and manipulated using appropriate software to determine constant offset values and to determine how closely the response curves relate to one another. This is done as the floating point precision is limited on the devboard compared to a computer to prevent any unnecessary time delays.

5.3.1 Raw Data Test Results

A graph is generated to represent the response curves of the various sensors using Microsoft Excel. This graph is shown in Figure 20. As expected the results show that the Control, Sharp sensors and APDS sensors have fairly linear responses while the SFH sensors have a logarithmic response curve.

Additional results and results relating to individual sensor types are documented in appendix D.3.

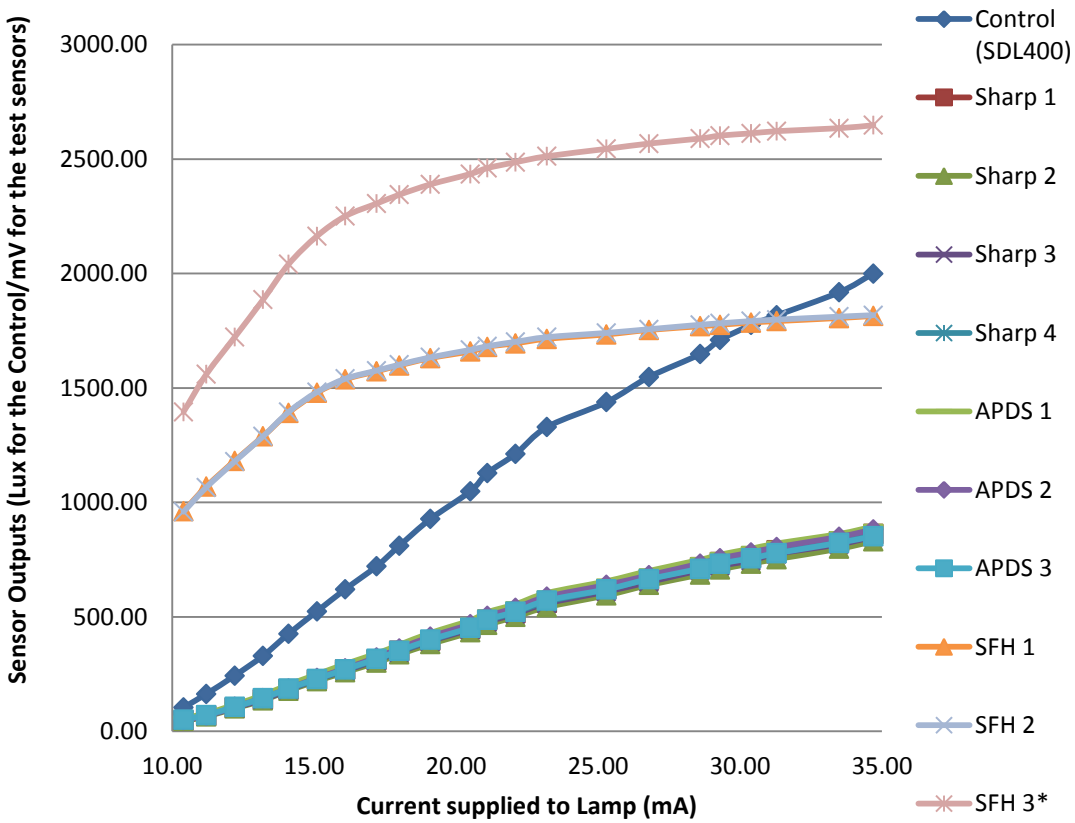

Figure 20: Raw Data Sensor Test Results for all Sensors

5.3.2 Processed Data Test Results

Once the raw data is collected it requires processing in order to convert the output values into lux values for comparison with the industry standard sensor.

For the two linear output sensor types the data from each sensor of the same sensor type was gathered together and viewed as whole. This was done in order to determine the processing required for the sensor type not for individual sensors so that a generic processing procedure could be applied to all sensors of that type resulting in the best overall results.

The data was analyzed to determine the maximum lux error, percentage error, lux range, lux error of mean and percentage error of mean of each sensor type at each measurement step. The maximum lux error refers to the maximum difference between any of the sensor measurements taken by sensors of the same type and that of the control sensor. The percentage lux error is the largest percentage difference between any of the sensor values of the same sensor type and the control sensor. The lux range is the difference experienced by sensors of the same type under the same conditions. The lux mean error is the error between the mean value measured by sensors of the same type and the control sensor. The percentage error of the mean is the percentage by which the mean value determined differs from that of the control. A summary of the resulting maximum errors can be seen in Figure 21.

Figure 21: Comparison of the Maximum Errors Occurring for Each Sensor Type

A constant linear offset value was determined using the Microsoft Excel Solver application to minimize the percentage lux error. This approach was selected as minimizing the maximum lux error may result in larger lux differences in the lower lux regions in order to minimize the differences at higher lux levels. This results in perceptible differences to the human eye. This can be highlighted by the argument that a difference of 50 lux from 100 lux to 150 lux will be highly perceptible whereas a change from 950 lux to 1000 lux will not be nearly as noticeable. Minimizing the percentage error therefore takes into account the scalable differences and is a better performance determining characteristic.

This constant offset value was then applied to each of the raw sensor measurements taken by any sensor of a specific sensor type. An extract from the spreadsheet used for this calculation is shown in appendix D.2 for the Sharp sensor analysis.

For the logarithmic response SFH sensor the transfer function was applied to the results and then a similar procedure was followed to that of the linear response sensors where the optimal constant offset value is found.

The manipulated results with the constant offset values applied to each measurement can be seen in Figure 22. In the figure it can be seen how closely the results of the various sensors correlate to those of the control sensor. For more detailed results relating to each sensor group, see the figures in appendix D.4

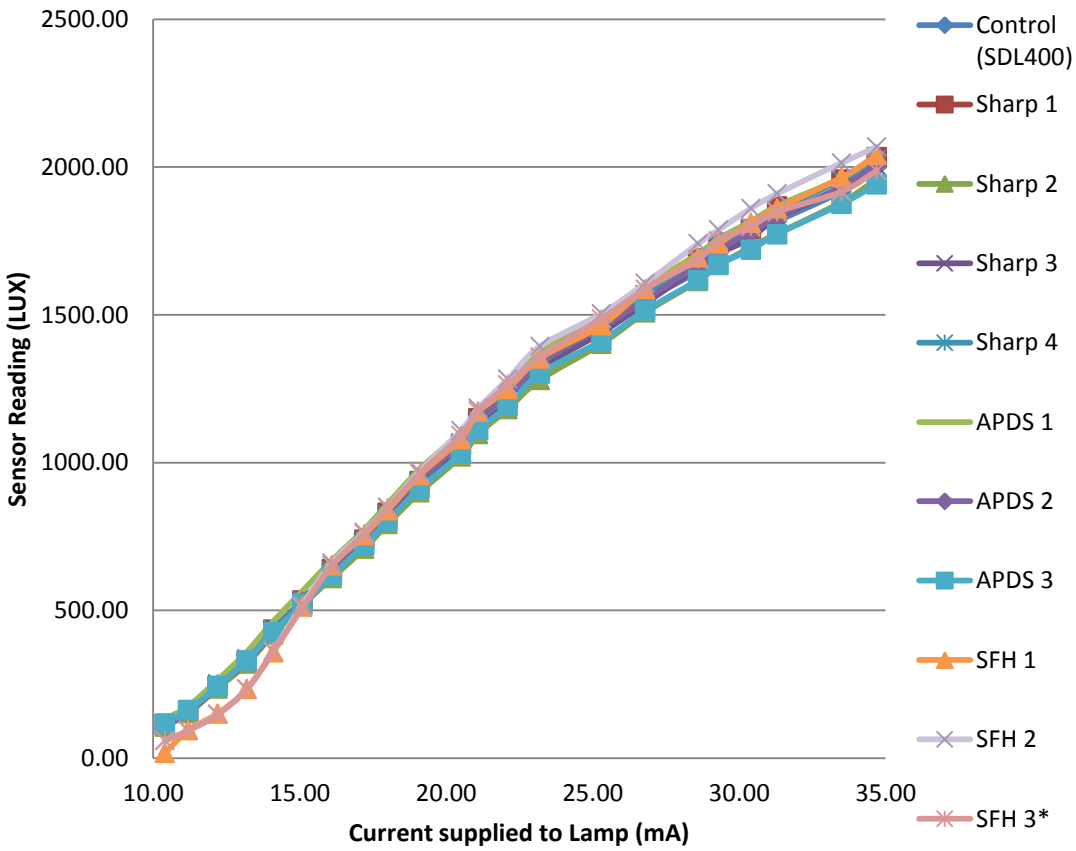

Figure 22: Manipulated Data Sensor Test Results for all Sensors

5.4 Concept Evaluation

Initial inspection of the results shown in Figure 20 and Figure 22 show that sensors of the same sensor type appear to be fairly consistent with one another following similar trends. The sensors also appear to correlate well with the control sensor once the constant offset manipulations are made, following the same trend line as that of the control. From Figure 22 it can be seen that the SFH sensors fair poorly compared to the other two sensors between 0 lux and 500 lux. From that point onwards it is fairly difficult to visually differentiate between the different sensors as their readings are all close to that of the control sensor and further investigation is required.

5.4.1 Sensor Results Comparison

One of the most important characteristics to take into account with regard to sensor selection is the accuracy of the sensor. This refers to the ability of the sensor to give the correct measurement value for a wide range of lux values. Various error values were determined for the sensor types tested at each of the different illumination levels between 100 lux and 2000 lux. The results are summarized in Figure 21. From this figure it can be clearly seen that the Sharp

sensor performs the best with a maximum percentage lux error of just less than 10%. In fact, in most cases the error was less than 5%.

In addition to the accuracy of the sensor it is important to take into account other characteristics of the sensors as discussed in section 4.4.2.

Most of the initial application requirements and general characteristics such as light source spectral characteristic, mating electronics, frequency bandwidth, toxicity, local availability, output type, spectral response, ease of customization and component type were primarily taken into account when selecting the initial list of sensor units to be tested.

The accuracy and the output response curves have been determined and discussed. Further investigation can now be done into the performance of the sensors relative to the cost and the sensitivity of the sensors.

In order to determine the sensitivity of each sensor the intensity of the light source was incrementally changed until a change occurred in the output of the sensor. This allowed the sensitivity of the sensor to be determined.

Table 6: Sensitivity of the Tested Devices

Light Sensor Unit	Sensitivity
Sharp GA1A2S100LY	7.62 lux
APDS-9005-020	7.35 lux
SFH 5711	NA*

*The sensitivity of the SFH sensor is not a constant value due to the logarithmic nature of the device.

The difference in sensitivity of the two linear output sensors is negligible as a difference of 0.27 lux is insignificant to the human eye under most circumstances.

With regard to performance relative to cost it is easy to see that the SFH component is inferior to the other two. It is the most expensive and performed most poorly under the required conditions. The APDS component was the cheapest (R3.06 cheaper than the Sharp component) and the Sharp component performed the best.

Despite the higher cost it was decided to use the Sharp component. The decision was influenced by the superior performance of the component seen in Figure 21 as well as the simpler construction associated with the though-hole component circuit. It was however decided to do further investigation into the Sharp sensor to determine the optimal load resistor for use in the desired system.

5.4.2 Sharp Sensor Evaluation with Varying Load Resistor R_L Values

The load resistor value of the Sharp 1 sensor was changed to determine the effect that the load resistor has on the sensor. This process was done in an attempt to

further optimise the output of the sensor for the desired lux values ranging from 100 lux to 1000 lux.

The adjusted load resistances resulted in the graph shown in Figure 23.

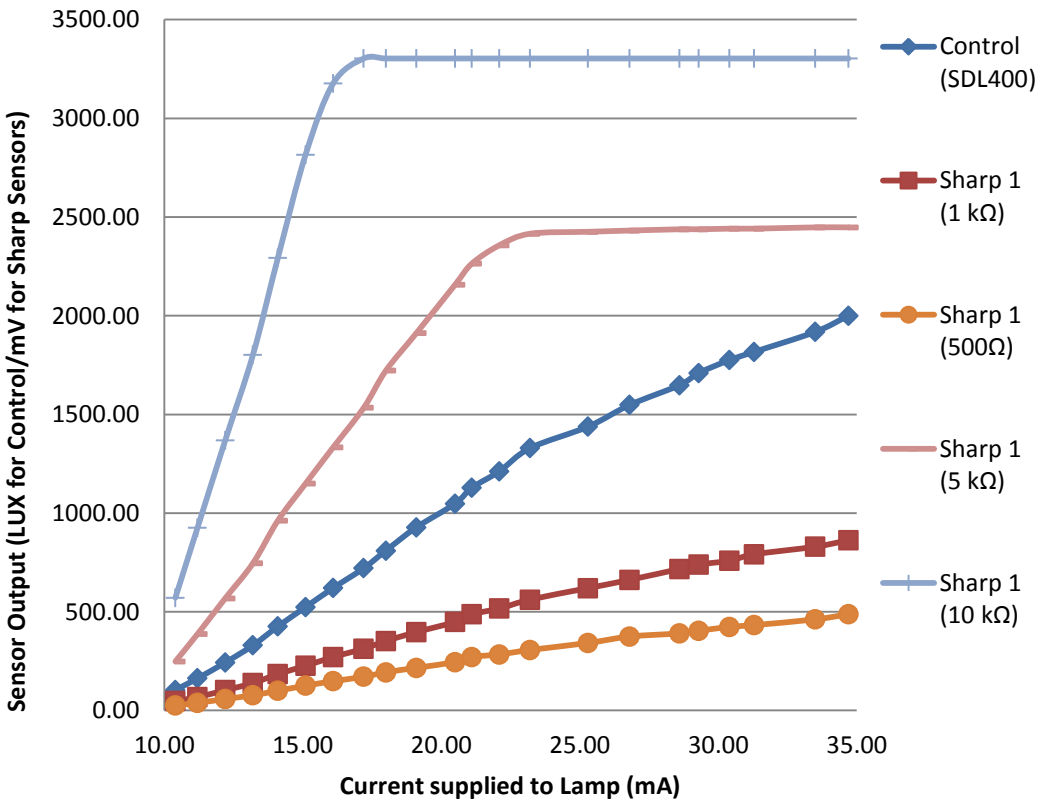

Figure 23: Raw Data Sensor Test Results for Varying Load Resistor (Rl) Values

From this graph the saturation point of the sensor can be seen for the load resistor values of 5 kΩ and 10 kΩ to be around 1200 lux and 600 lux respectively. In addition to this the saturation values for the 500 Ω and 1000 Ω were found to be 4500 lux and 3800 lux respectively. These values can be used to generate an approximate trend line, shown in Figure 24.

The ideal saturation point for the sensor would occur at 1000 lux as this is the upper limit of the range with which we are concerned. Applying a safety factor of 1.5 to this leaves us with a theoretical saturation point of 1500 lux in an attempt to ensure that linearity of the sensor output extends well past the region of 1000 lux. The generalized trend line established can be used to estimate that a value of 2588 Ω for the load resistor will result in sensor saturation at approximately 1500 lux. The closest standard resistor value is 2700 Ω and is therefore selected. To confirm the estimation a test procedure conducted with the 2700 Ω was done to determine the saturation point.

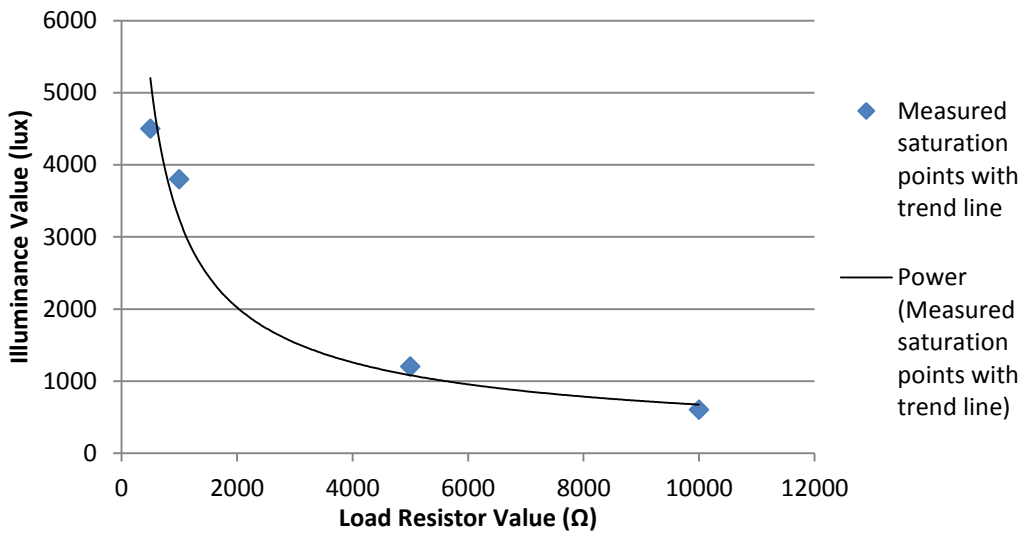

Figure 24: Sensor Saturation Point trend Line

The same test procedure done for the sensors earlier was followed. The resulting output response curve is shown in Figure 25. This shows that the output value of the sensor does indeed begin to drop below that of the control above 1500 lux indicating that saturation of the sensor has begun and the linearity of the sensor is deteriorating as expected.

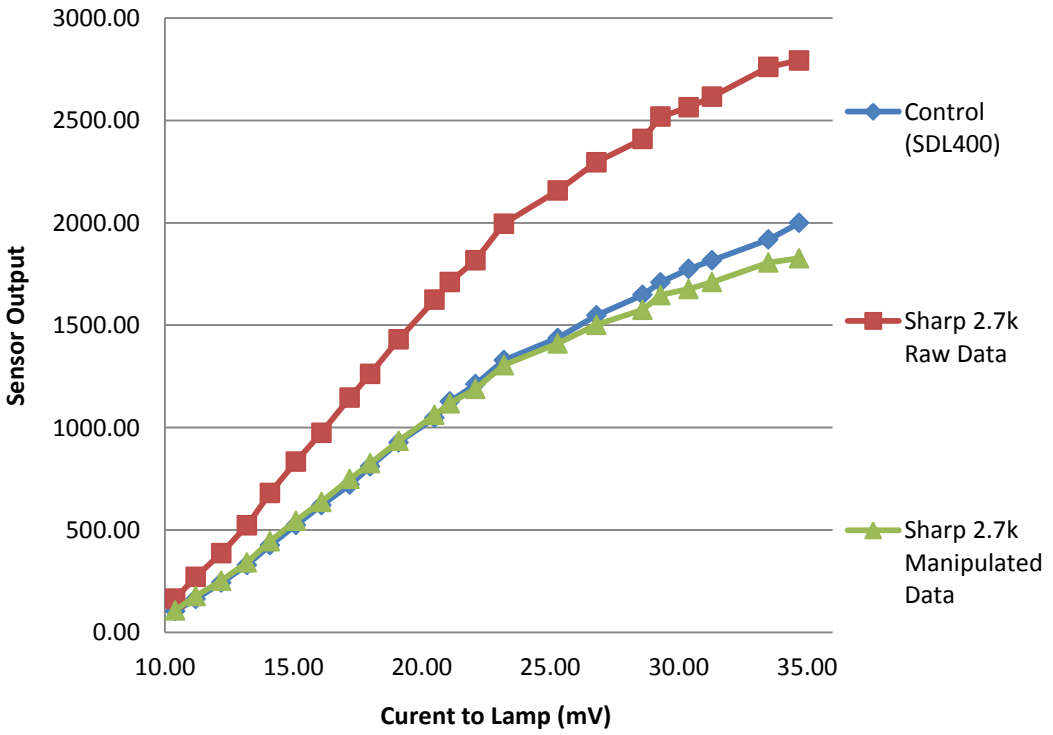

Figure 25: Output Response Curve for the Sharp Sensor with a 2.7k Load Resistor

6 PROTOTYPE DETAIL DESIGN

As with the conceptual design a microprocessor system will be required to perform and fulfil the requirements of the prototype design. The central node design selected previously in section 4.2.3 is used for the prototype system design. A simplified schematic of the expected system, which is an extension of the conceptual design, is shown in Figure 26 documenting the expected interactions between components.

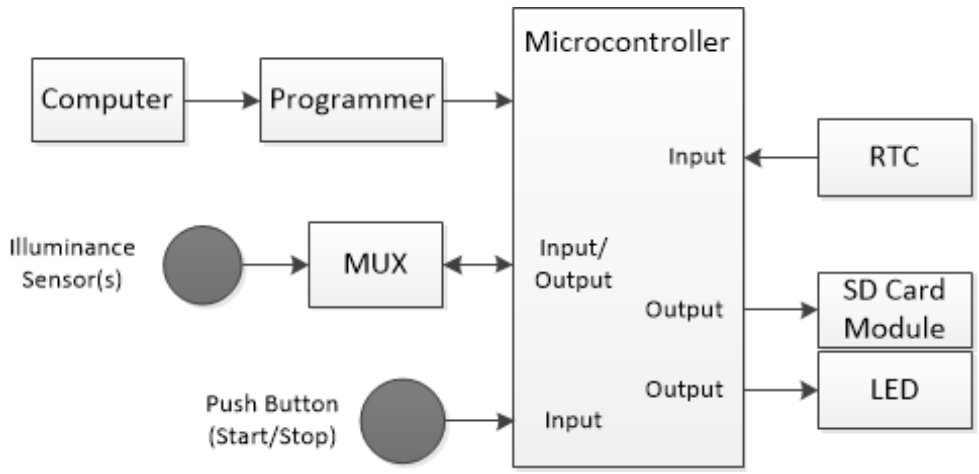

Figure 26: Simplified, Complete Representation of the Microcontroller Based Illuminance Sensing System used for the Project

6.1 Prototype Overview

The control of the system as well as each component of the system was developed and chosen in an attempt to optimise the efficiency and performance of the system as a whole while keeping costs to a minimal. A detailed analysis of the system layout, component interaction and functionality used for the prototype is presented in the following sections. Once again an iterative process of analysis, synthesis and evaluation was followed in the process of creating the prototype system design.

The central node multiple sensor design utilises the PIC18F8722 development board as the central node to control all system interfacing, sensor control and data aggregation. The use of the devboard in the prototype system design is described in further detail in section 6.2.

A total of 64 illuminance sensors interface with the central node through hard wire connections, so that measurements from each can be taken and recorded. The final sensor design is documented in section 6.3. The outputs from the sensors are read and converted by the Analog-to-Digital Converter (ADC) before being recorded and stored on a memory card for easy data manipulation and processing post data collection as documented in section 6.4. The sensors interface with the

central node through mux assemblies due to the number of sensors exceeding the number of available ADC channels on the devboard. The multiplexer (mux) assembly interface is documented in section 6.5. It is found that an external power supply circuit will be preferential for the system and the development of this is documented in section 6.7.

A simplified schematic of what the complete system will look like and how it will interact is shown in Figure 27.

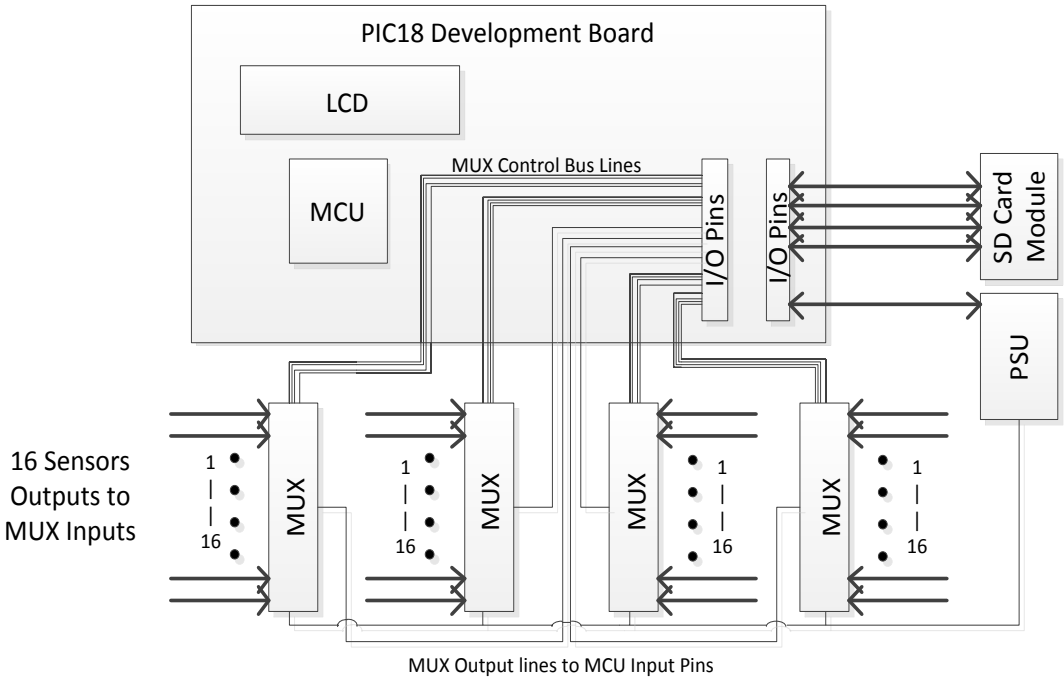

Figure 27: Simplified Prototype System Layout Schematic

6.2 PIC18F8722 Development Board

The selection of the central node is well documented in section 4.4.1 with the advantages of the selected development board well established.

The use of the central node is fundamentally the same for the prototype design as it was with the concept design; to control all system interfacing, sensor control and data aggregation. However, for the prototype design the central node must be able to perform these functions in a more complex system interacting with far more than a single sensor and LCD display as was done in the concept design.

This was anticipated during the initial selection of the PIC18F8722 as the central node and it will therefore be able to meet the requirements.

A vital characteristic of the devboard is to be able to interface with the large number of sensors required. It is impossible to have each sensor attached to a

single ADC channel due to the limited number of ADC channels available. However it is possible to use multiplexer assemblies to minimise the required ADC channel number. The devboard has 16 ADC channels, some of these are pre-assigned to on-board functions or are initialised for other operations involved with the SD card module. From literature and from experimental testing it was found that 9 of the channels, AN(6,7,8,9,10,12,13,14 and 15) are available for use in the system design.

This will allow the system requirements to be met with the use of multiplexer arrangements.

6.3 Illuminance Sensor

As determined previously the Sharp GA1A2S100LY sensor with a load resistor of 2700 Ω meets the requirements of the project and was selected for use in the prototype design.

The basic circuitry will remain the same as discussed previously however for ease of assembly and for consistency a Printed Circuit Board (PCB) was created for the circuit. The circuit also includes a connector point for the cable connector attachment as well as male output pins for debugging purposes. The cable connector was chosen to be a right angle connector to prevent any shadows from vertical connectors or cables from interfering with sensor measurements. The PCB schematic can be seen in Figure 28 with the PCB layout shown in Figure 29.

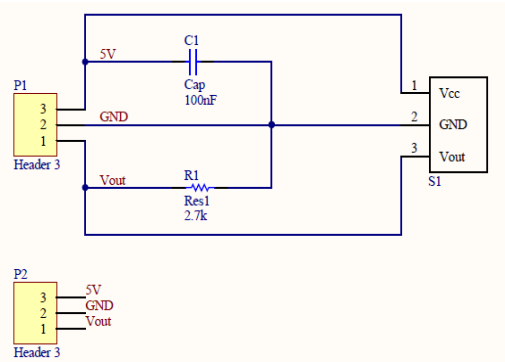

Figure 28: PCB Schematic for the Sensor Circuit

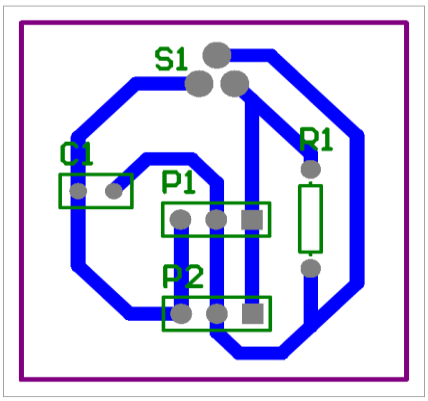

Figure 29: PCB Layout for the Sensor Circuit

Additionally 4 rubber feet are attached to the underside of the sensors. This was done for a few reasons. They provide a sturdy level platform for the sensor assembly so that the balance is not offset by protrusions such as solder. They help to reduce the ability of the sensor to slip to a new location. Finally, they prevent the circuits from shorting as the solder at the bottom will not touch ground or be able to connect to each other through the surface on which they are placed.

The completed PCB with sensor and components is shown in the top view and bottom view images seen in Figure 31 and Figure 30 respectively. The clear feet can be seen in the bottom view image.

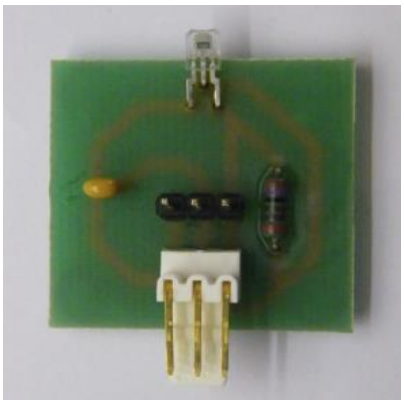

Figure 30: Top View of Completed Sensor

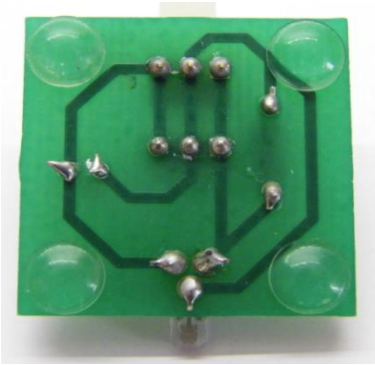

Figure 31: Bottom View of Completed Sensor

6.4 Data Storage Method Selection

Data storage was not required for the concept sensor testing section however the prototype system will require a method of data storage where measurements taken by the numerous sensors can be stored and later accessed for further processing.

A flash memory card (commonly known as a memory card) is a solid state electronic data storage device which has the ability to save stored data after power

has been disconnected from the memory device (Ibrahim 2010). This ability in conjunction with the potential for large storage capacity makes it perfect for the system requirements.

Many different types of memory cards are available with the secure digital (SD) card probably being the most widely used (Ibrahim 2010). The PICtail Daughter Board for SD and MMC cards, shown in Figure 32 plugs directly into the PIC18 development board enabling simple interface between the board and an SD Card. The standard SD card facilitates easy data storage and retrieval with compatibility with most computers.

Figure 32: PICtail Daughter Board for SD and MMC Cards

With the use of an SD card module data can be recorded in the form of a comma-separated values (CSV) list in a text file following the completion of on board analogue to digital conversions. Any data handling or processing can then simply be done with the use of a PC with appropriate software (such as Microsoft Excel or MATLAB).

The layout of the text file (.txt file) will include the date and the time-stamp of the data entry, followed by the recorded sensor values before starting a new line. The expected layout representation is shown as:

"Date Time1 , Sensor 1 Value, Sensor 2 Value, Sensor 3 Value, …

Date Time2 , Sensor 1 Value, Sensor 2 Value, Sensor 3 Value, …"

6.5 Multiplexer Assembly

The desired number of sensors for the system far exceeds the 9 available ADC channels therefore, as stated in the prototype overview, it was determined that multiplexer assemblies would be required. With 9 available channels, either 8-to-1 or 16-to-1 multiplexer assemblies will suit the system requirements.

The sensors are analogue output components so the multiplexer required is an analogue multiplexer. A CD74HC4067, 16-to-1 analogue multiplex with the data

sheet extract shown in appendix A.7 was selected for use in the system. The simplified depiction of the multiplexer operation is shown in Figure 33. The completed multiplexer assembly design can be seen in Figure 34.

In the figure 'A' is the multiplexer itself. 'B' is a 0.1uF bypass 'smoothing' capacitor added to reduce noise interference with the output signal. 'C' shows the location of the output signal and V_{cc} pins. 'D' shows the location of the control line pins; made up of the four select lines, enable line and ground line pins. Finally 'E' shows the test point pins added to the design for debugging purposes.

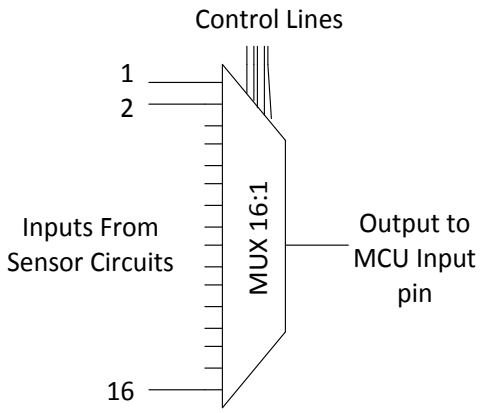

Figure 33: Basic Operation of 16:1 Multiplexer

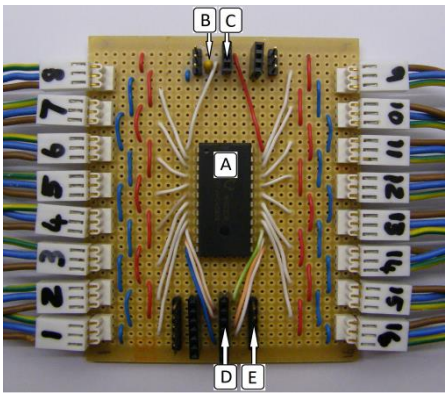

Figure 34: Multiplexer Assembly used in Project

6.6 Sensor Connector Cabling

In order to ensure that cabling used to connect the sensors and the development board would not affect the output of the sensors the cable selection was carefully considered. In the end a H03VV-F 2183Y 3 Core 0.5mm Black Cable was selected. The cable is a flexible 3 core cable ideal for the sensor application as V_{cc}, GND and OUTPUT signals have to be transmitted.

The ends of the cables are stripped and crimped before connecting a Molex 2.54 mm 3-way housing 4809, female cable connector. The three-way cable connector can then be attached to its corresponding Molex 2.54 mm 3-way gld f-lck r/a hdr, male connector mounted on the sensor boards or on the multiplexer assemblies. A finished cable with female cable connector can be seen in Figure 35.

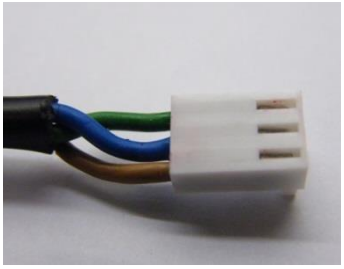

Figure 35: Example of the Cable Connector

This cable has a rated resistance of only 39 Ω/km and as sensors would only be attached to cable lengths of 2 meters this resistance is assumed negligible. In order to confirm this, a single sensor was tested with varying lengths of cable under the same illumination conditions. With the distance changed from a maximum of 5 m to a minimum of 30 cm, no discernible change was detected.

6.7 Power Supply

The PIC18F8722 development board has its own power supply to operate all on-board requirements. However the addition of a large number of sensors to the power supply may cause power supply problems for components of the board. It was therefore decided to make use of a simple external power supply unit to power the sensors separately.

A readily available and affordable Ansmann APS 2250 H, 12-24V universal power supply was selected as it would easily supply the rated current of all sensors. The power supply is operated with 12V and 2A. A LD1117-TO-220, 3.3V regulator was selected and built into the regulator circuit shown in Figure 36.

An extract of the data sheet for this component is shown in appendix A.6. The 2 capacitor values required in the power supply circuit are shown in Figure 36. The ground connection of the circuit is supplied from the common ground of the development board.

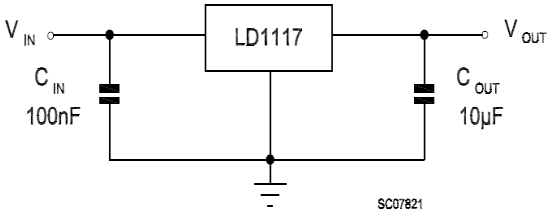

Figure 36: External 3.3V Regulator Circuit (Extract from the Regulator Data Sheet)

6.8 C Software Develompent for Prototype System

The same software used for the illuminance sensor development is used for the prototype system. The main method outlined in Figure 37 is developed using this software. The C code developed for the prototype system is shown in appendix B.2.

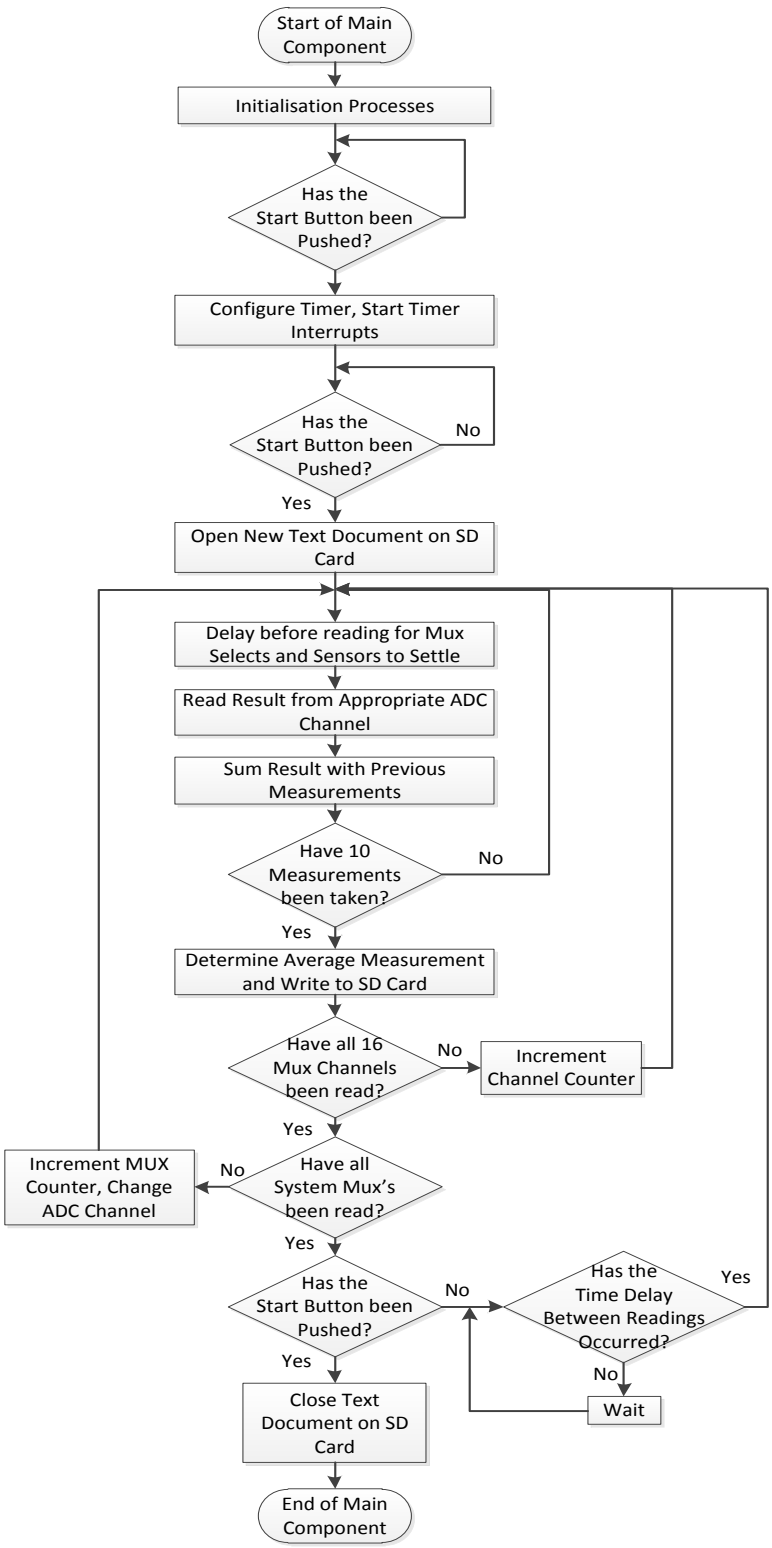

Figure 37: Main Method for Prototype Development

The initialisation process involves the initialisation of variables, configuration of parameters such as those associated with the use of the ADC and the configuration of the various ports and pins required by the system.

The program then waits for an external interrupt in the form of a push button to be activated. Once it is pushed the program loads the time to the timer and begins to generate timer interrupts required to keep track of time between measurements. The system then waits again for an external push button interrupt to occur signalling the start of the data recording process. A text document (.txt) is created on the SD card where data will be stored as a CSV list.

Measurements then begin recording and as before an average value is determined however the number of measurements used for the average has been reduced to 10 as the use of 100 proved to be excessive. The measurements are taken within nested for-loops which allow the system to run through each mux channel for a single mux assembly before moving to the next mux assembly and reading all those channels. Care is taken to ensure that a delay occurs between readings so that the 1000 ns rise and fall time as well as any other propagation delays associated with the mux, ADC and other components do not influence the measurements. A delay command "Delay1KTCYx (240)" is used to provide a 20 ms delay, far exceeding any internal processing delays.

If a full sequence of measurements has been taken the system pauses until the time required between measurements has elapsed. The next iteration of data recording is then initiated unless the external push button has again been pushed. If this happens the system will halt data collection before a new iteration of measurements is started and will close the text document allowing for the safe removal of the SD card from the PICtail Daughter Board for use in further data handling and data processing.

6.9 Prototype Parts List and Costing

In order to accurately analyse and evaluate any system it is required to know the full cost associated with the development of the system. This section breaks down the system as a whole into its various components and documents the costs associated with each.

The cost breakdown is focused on the completed prototype system as this is the system that is designed to meet the requirements of the project description.

The complete system is comprised of the following:

The central node consisting of the PIC18F8722 Development Board, the PICkit3 programmer/debugger and the 9V PSU.

The data logging aspect of the system includes the PICtail SD card module and the SD card itself.

The 64 illuminance sensor circuits each consist of the sensor circuit PCB, a sensor, a 0.1uF capacitor, 3 male header pins, a three-way male cable connector, a 2.7 kΩ resistor and 4 rubber feet.

The power supply circuit contains the 12V, 2A power supply, 2 capacitors of 100nF and 10uF, a 3.3V regulator, 2 female header pins and finally the vero board on which the circuit is constructed.

The 4 multiplexer assemblies each consist of a multiplexer, 16 three-way male cable connectors, 18 male and 18 female header pins, a single 0.1nF capacitor, wire to form connections in the circuit and the vero board on which the circuit is constructed.

Software required for the prototype design includes the MPLAB C18 C compiler and the MPLAB IDE. It is assumed that the system user will have Microsoft Excel readily available and will have a means to graphically represent the data collected.

The cabling required to connect the sensor circuits with the multiplexer circuits consists of a 1.5 m cable length with three-way female connectors on each end. Each end therefore also requires 3 cable crimping fittings which fasten each of the three cable cores into the three-way connector.

Finally connector cables between the multiplexer circuits and the devboard as well as the power supply unit and the devboard need to be accounted for. These connectors include 3 6-way ribbon cables and approximately 20 male-to-male connector cables.

The breakdown of the costing for the entire system is shown in Table 7. It can be seen that the prototype design required R6 216.09 worth of hardware and software to be developed.

This value is significantly lower than a similar commercially available system which was quoted at above R40 000.00 with additional fees of above R5 000.00 per illuminance sensor, which totalled well above R350 000.00 for a system with 64 sensors.

Table 7: Cost Breakdown of the Prototype System Design

System Position	Component	No. Units	Cost/Unit (excl VAT)	Total Cost (excl VAT)
Central Node	PIC18F8722 Development Board	1		
	PICkit3 programmer/debugger	1	R1971.47	R1971.47
	9V PSU	1		
Data Logging	PICtail SD Card Module	1	R524.01	R524.01
	SD Card	1	R99.00	R99.00
Illuminance Sensor Circuits	PCB	64	R583.68	R583.68
	GA1A2S100LY Sensor	64	R12.22	R782.08
	Capacitior (10uF)	64	R0.84	R53.76
	Resistor (2.7 kΩ)	64	R0.08	R5.12
	Rubber support foot	256	R0.47	R120.32
	Three-way male cable connector	64	R2.10	R134.40
	Male header pin	192	R0.10	R19.2
Power Supply Circuit	12V, 2A power supply with barrel jack	1	R408.94	R408.94
	Capacitor (10uF)	1	R0.84	R0.84
	Capacitor (100nF)	1	R0.84	R0.84
	3.3V Regulator	1	R13.74	R13.74
	Female header pin	2	(For 10) R1.63	R0.33
Multiplexer Assemblies	16-to-1 Multiplexer	4	R24.00	R96
	Three-way male cable connector	64	R2.10	R134.40
	Male header pin	72	R0.10	R7.20
	Female header pin	72	(For 10) R1.63	R11.74
	Capacitor (100nF)	4	R0.84	R3.36
Cabling	3 Core 0.5mm Black Cable H03VV-F2183Y	100m	R852.28	R852.28
	Three-way female cable connector	128	R0.55	R70.40
	Wire core crimp connectors	384	R0.30	R115.2
Software	MPLAB C18 C compiler	1	Free	Free
	MPLAB IDE	1	Free	Free
Miscellaneous	6-way Ribbon Cable	3	R7.79	R23.37
	Male-to-male connector cable	20	R2.94	R58.78
	Vero Board	2	R125.63	R125.63
			Total:	**R6216.09**

7 PROTOTYPE TESTING

The system prototype developed should measure illuminance values up to a maximum of 1500 lux at multiple locations, within an interior area, simultaneously and record the results. The recorded data should then be easily extractable for processing, analysis and visualisation. To determine the extent to which the prototype meets the requirements the following prototype testing was conducted.

7.1 Testing Location Set-up

The location for the testing of the prototype system was selected to be a 2m x 2m room built on the solar roof of the Stellenbosch Engineering building. The room was specifically constructed for the testing of light pipe and collimator installations as part of the initial project documenting the design, installation and testing of a daylighting system for a rural South African classroom from which this project evolved.

The room has two light pipes, one centered on the roof and the other one located near the right corner of the roof as shown in the actual testing facility seen in Figure 38.

Figure 38: Actual Testing Facility

The interior walls of the room are covered in black material to reduce unnecessary glare and reflections leaving only the variations in light distribution created by the light pipes themselves.

The distance between the floor and the ceiling is designed to be an approximation of the distance between most office desk levels and that of the office ceiling so that the amount of light recorded in the test room will be equivalent to that which would be experienced by a desk user.

It was felt that this room would be appropriate for testing as the daylighting implementation currently in place is a perfect example of a daylighting implementation for which this project was visualized. It is the analysis, development and improvement of daylighting systems such as this that the project is designed to be used in conjunction with in future.

The light pipes allow natural light into the room. The illumination is expected to continuously change in spatial and time domains with respect to the working area as the time and weather conditions change. To further enhance the light variations it was decided to conduct testing without the inclusion of the collimator, which is designed to evenly distribute light into the interior from the light pipe installation. This will test the ability of the prototype to record and display how the light variations occur.

7.2 Testing Procedure

As a proof of concept it was decided to first ensure that an assembly of 16 illuminance sensors connected to a single multiplexer unit would record data over a period of time within the illuminated area. This is the minimum resolution stipulated in the design requirements. Once the correct operation of the system is verified the system can be upgraded to 64 sensors.

The prototype system sensors are set-up in a uniform distribution within the room. Care is taken to ensure that no cable blocks the field-of-view of any other sensor and that each sensor is level with an unobstructed view upwards.

The program is initiated with a push button on the devboard which begins system operations as discussed in 6.8. Data from each sensor is recorded and time-stamped in the .txt file on the SD card every 5 minutes. The time between measurements can be easily changed by simply changing the value of the delay time required. An example of such a file for a single MUX assembly (16 sensors) can be seen in appendix E.1 with an example of the full 64 sensors shown in appendix E.2.

Once operations have been halted by pushing the push button again the SD card is removed and placed in a compatible computer SD card module so that the data can be accessed. The data is exported into an excel spreadsheet where it undergoes processing. The processing required is simply to apply the constant off-set value determined during sensor testing to the sensor output values. The constant is applied to each data entry to ensure continuity and accuracy. An example of an Excel spreadsheet before and after processing, for 16 sensors, can be seen in appendix D.5. The process for 64 sensors is exactly the same however, the spreadsheet is larger with 64 sensor columns.

The data is now expressed in terms of lux and can be used to accurately depict the illumination levels in the room. The data can now be utilized to visually depict the

room by use of appropriate software. This can be done using Excel itself or other packages such as Matlab.

It was decided to use Matlab for this project. With Matlab it is possible to fit a surface of the form $v = f(x, y)$ to data given the vectors (x,y,v), where the function interpolates the surface from the known values. The vectors x and y are the positions of the measurement locations while v is the measurements themselves. The generated surface always passes through the defined data points.

The method of interpolation used for the project is a triangular based natural neighbour interpolation method. This supports both 2D and 3D interpolation and is an efficient tradeoff between linear and cubic interpolation methods.

An example of Matlab code that can be used to analyze the data for 16 sensors is shown in appendix C.1. The code can be easily edited to accommodate 64 sensors. The code for 64 sensors is shown in appendix.C.2.

7.3 Prototype 16 Test

The test area is divided into a grid format of 16 squares making up the room with a sensor at the center of each square. This arrangement is shown in the system layout shown in Figure 39, as well as seen in practice in Figure 40

The prototype is tested under both clear sky and overcast overhead conditions.

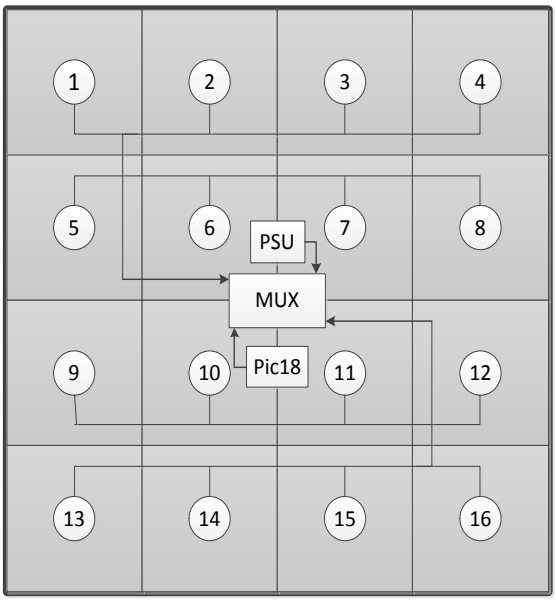

Figure 39: Prototype 16 Sensor System Layout

7.3.1 Prototype 16 Overcast Testing Results

During overcast conditions it is assumed the natural light entering through the light pipes is fairly uniform with no dramatic areas of glare or bright spots. The central light pipe is assumed to let in light evenly over the entire testing facility with the lower right hand light pipe illuminating the area below it more than the area on the other side of the room. The combination of the two pipes leads to the assumption that the lower-right quadrant of the room will be illuminated more than the rest. A picture of the interior of the testing facility under overcast sky conditions is shown in Figure 40 which tends to support this assumption.

Using the system recorded data and the processing method previously described, the comparison shown in Figure 40 is generated. The limit of 1500 lux on the illuminance range is established as the limit of the linear sensor range.

The image appears to follow the trend of the actual facility illumination but it is difficult to discern differences in the illumination levels. A second image is therefore generated with a limit of just 700 lux in an attempt to highlight the differences in illumination levels.

This image can be seen in Figure 41. From this image it is far more evident that the measured results mimic the actual interior conditions.

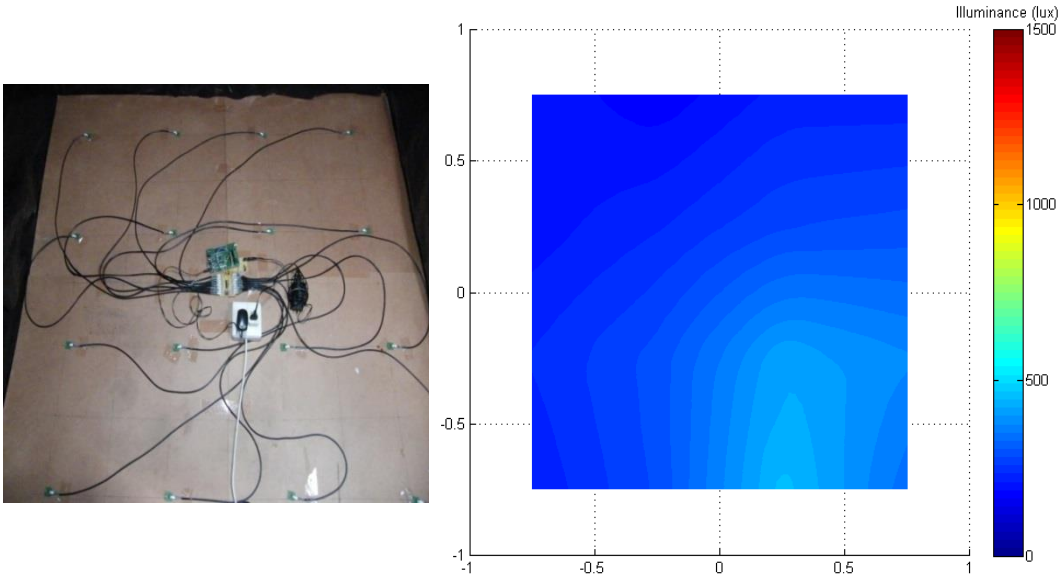

Figure 40: Comparison of the Testing Location and the Visual Representation of Sensor Measurements under Overcast Sky Conditions for 16 Sensor Set-Up

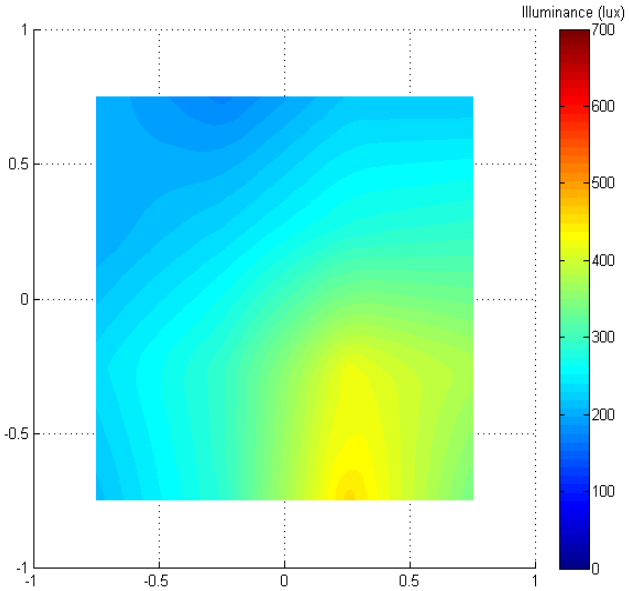

Figure 41: Visual Representation of Overcast 16 Sensor Measurements with Scale Limited to 700 lux

7.3.2 Prototype 16 Clear Sky Testing Results

Under clear sky conditions, with no collimator or diffuser in place, it is assumed that there will be large areas of excessive illumination resulting in glare and bright spots, therefore, creating unacceptable illumination conditions for a working environment.

The interior of the testing area under clear sky conditions can be seen in Figure 42. The areas of excessive glare are clearly visible in the figure.

Further investigation reveals that the crescent shape seen in the figure moves from the left of the room towards the right of the room as the day progresses.

Using the system with 16 sensors, under clear sky conditions, results in images such as the one shown in the comparison shown in Figure 42. When comparing the actual location image to the generated image it is not immediately clear that the two correlate. With the coarse 4x4 grid of sensors only 4 sensors in total are illuminated by the crescent area of glare. This leaves the interpolation of the data unable to accurately represent the correct pattern of over illumination.

With only 16 sensors available the resolution of the measurements is fairly poor, resulting in difficult to interpret images where the correlation between the measured results and the actual conditions is not immediately evident.

The results so far are, however, considered positive as they have shown that the system is able to perform correctly and can provide easy to understand graphic outputs despite the output under clear sky not correlating to the actual conditions within the room.

The addition of more sensors, improving the resolution, is expected to improve the correlation between the actual conditions and the generated image from measured data, particularly under clear sky conditions.

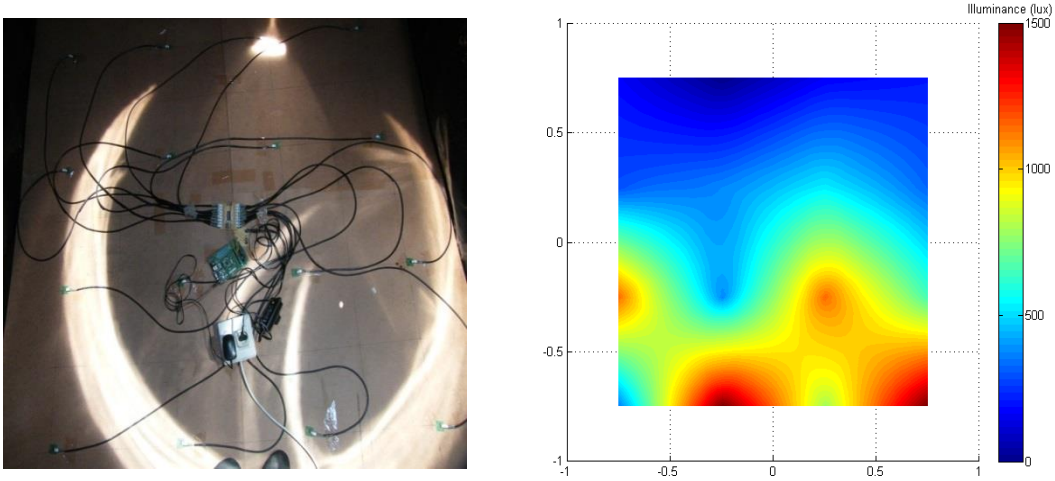

Figure 42: Comparison of the Testing Location and the Visual Representation of Sensor Measurements under Clear Sky Conditions for 16 Sensor Set-Up

7.4 Prototype 64 Test

From the positive results shown by the 16 sensor design it was validated that a larger array of sensors should be used to improve the resolution of the measurements in an attempt to increase the visual accuracy of the results specifically under clear sky conditions.

The test area is divided, in a similar fashion to the 16 sensor set-up, into a grid format of 64 squares making up the room, with a sensor at the center of each square. This theoretical arrangement is shown in the system layout shown in Figure 43, with the actual layout seen in Figure 46 to Figure 50.

The prototype 64 sensor system is tested under both clear sky and overcast overhead conditions as was done with the 16 sensor design

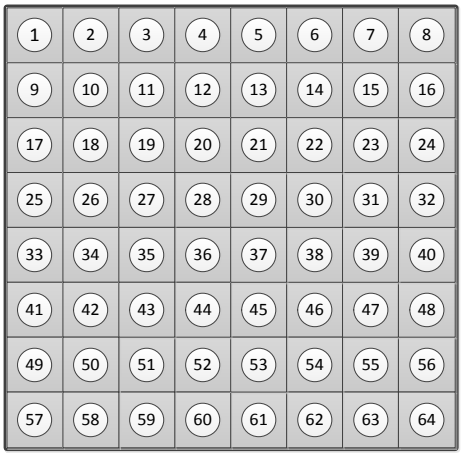

Figure 43: Prototype 64 Sensor System Layout

7.4.1 Prototype 64 Overcast Testing Results

For the overcast sky conditions the same assumptions hold true as for the 16 sensor test.

The resulting image for overcast conditions is shown in Figure 44. This image closely relates to the results obtained with 16 sensors and confirms the assumptions regarding the illumination of the interior of the test area. Due to the uniform nature of light entering the area under overcast conditions, the illumination within the room remains fairly constant over time unlike with clear sky conditions.

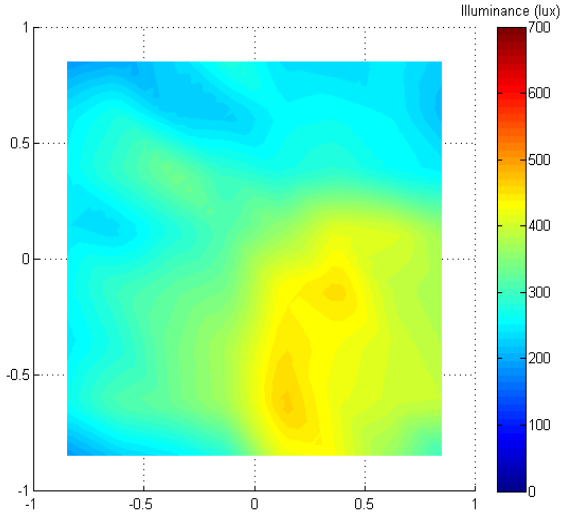

Figure 44: Visual Representation of Overcast 64 Sensor Measurements with Scale Limited to 700 lux

7.4.2 Prototype 64 Clear Sky Testing Results

Testing under clear sky conditions is expected to show the greatest difference between the 16 and the 64 sensor set-ups. The 16 sensor system provided poor performance under clear sky conditions. Therefore, the measurement resolution was increased to 64 sensors. The correlation between the actual location characteristics and the measurement generated image is expected to be much closer and clearer than it was with the 16 sensors.

A comparison of the progression of light within the location is shown from Figure 46 to Figure 50 for the period extending from 10:45 to 13:45 on a completely clear sky summer's day.

The large areas of over illumination and glare are clearly visible in the actual location pictures with the progression of the main, crescent pattern seen to be from the left of the test area, across the test area to the right hand side as time elapses.

The images generated from the measured results show a very close correlation with the actual illumination characteristics. The shape of the bright areas is clearly represented and visible during the progression and the progression accurately tracks the movement of the illumination throughout the time period.

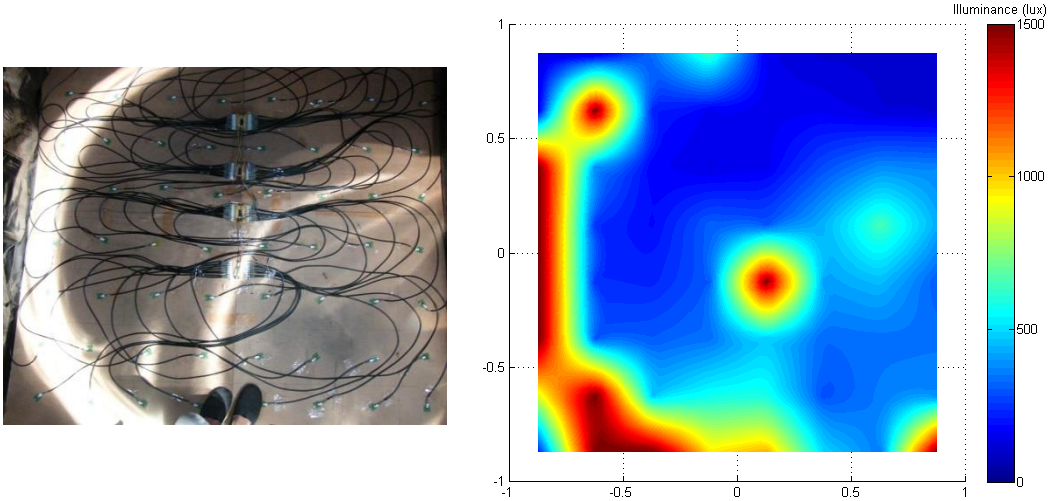

Figure 46: Comparison of the Testing Location and the Visual Representation of Sensor Measurements under Clear Sky Conditions for 64 Sensors at 10:45

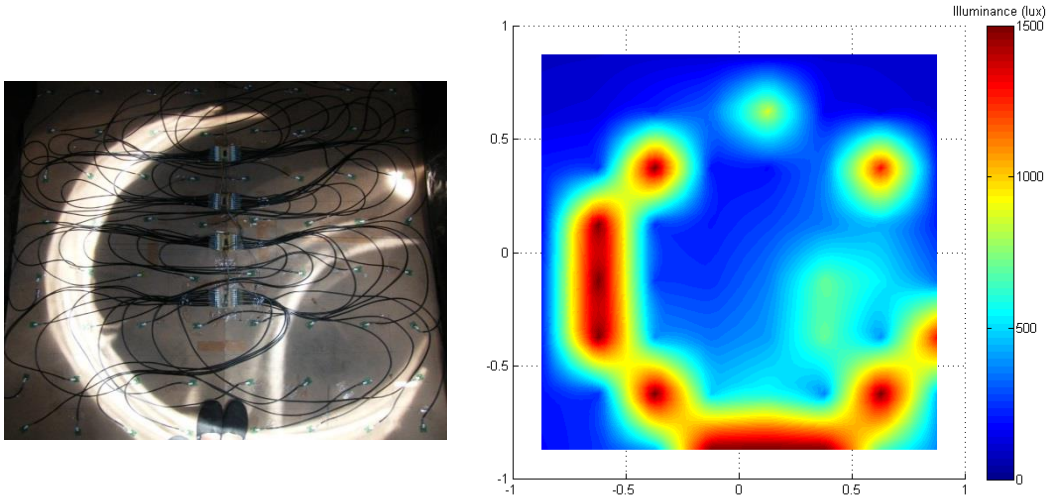

Figure 45: Comparison of the Testing Location and the Visual Representation of Sensor Measurements under Clear Sky Conditions for 64 Sensors at 11:15

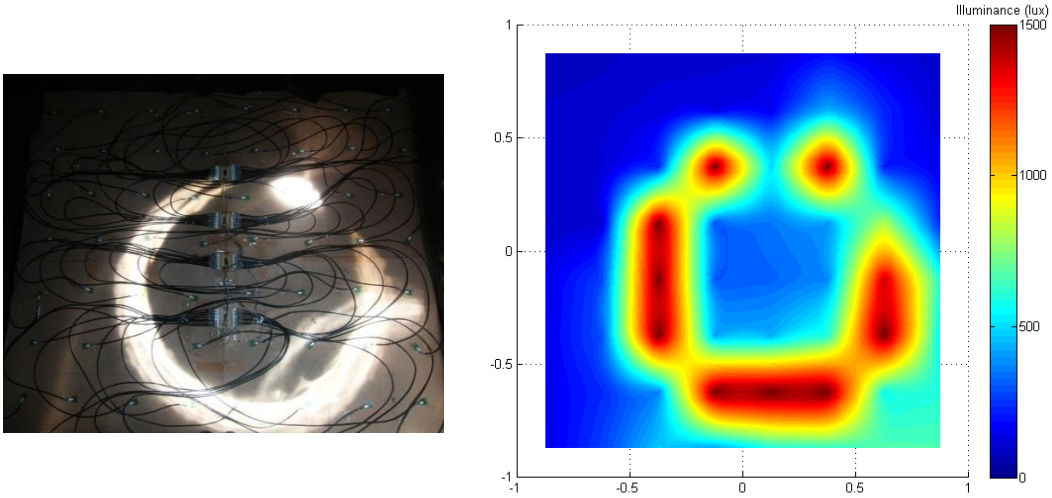

Figure 48: Comparison of the Testing Location and the Visual Representation of Sensor Measurements under Clear Sky Conditions for 64 Sensors at 11:45

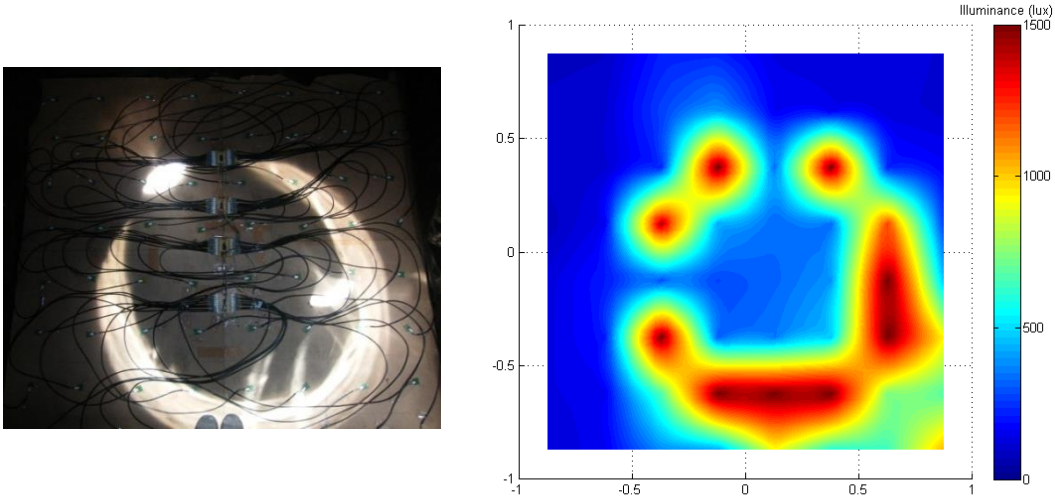

Figure 47: Comparison of the Testing Location and the Visual Representation of Sensor Measurements under Clear Sky Conditions for 64 Sensors at 12:45

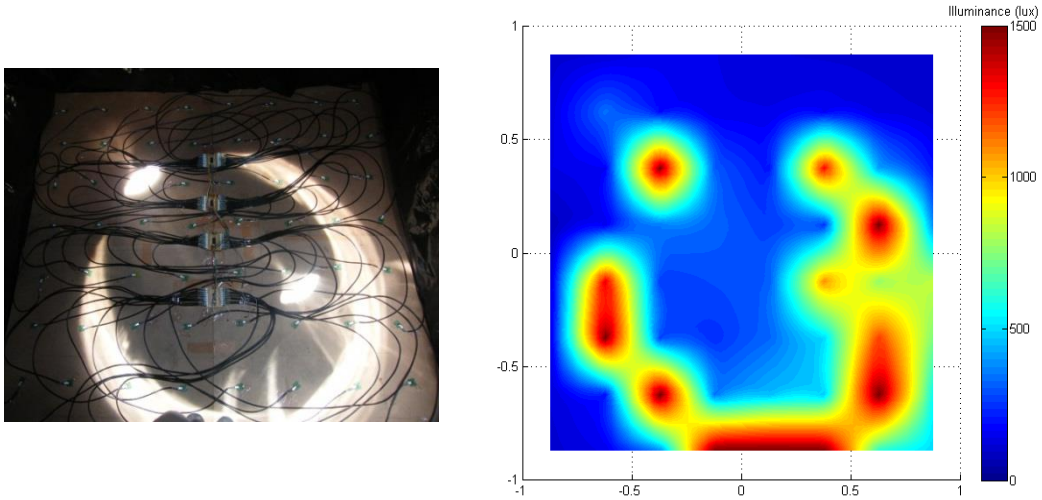

Figure 49: Comparison of the Testing Location and the Visual Representation of Sensor Measurements under Clear Sky Conditions for 64 Sensors at 13:15

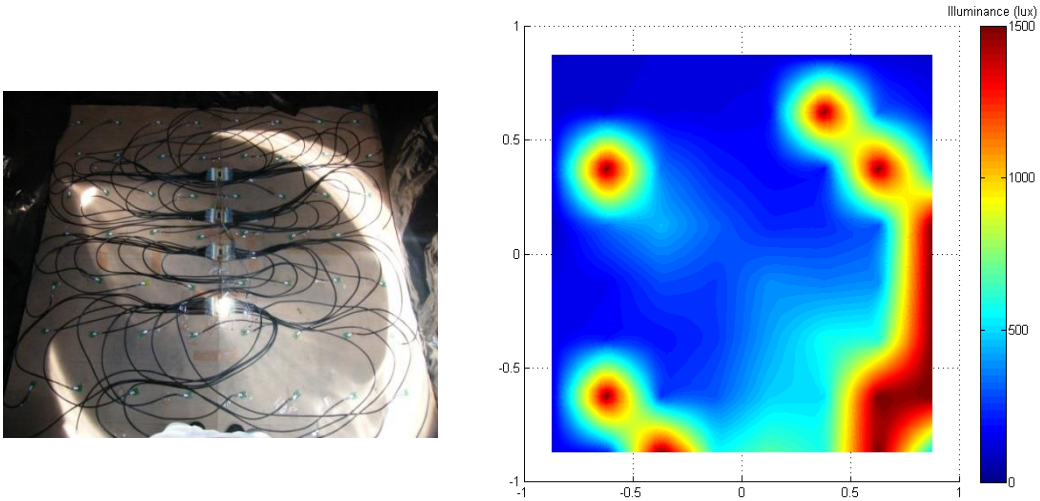

Figure 50: Comparison of the Testing Location and the Visual Representation of Sensor Measurements under Clear Sky Conditions for 64 Sensors at 13:45

7.5 Post Testing Calibration

The prototype system developed was tested over a long period of time. To ensure correct operation of the sensors a calibration test similar to those done before the testing began was done to each sensor.

The testing procedure showed that the performance of each sensor had decreased slightly. The sensors produced results that ranged between 3% and 18% below what they originally measured.

The reason for this is that the sensors were unprotected and exposed to the elements at times during testing resulting in the sensor surfaces becoming soiled and the sensors developing a brown, corrosive deposit around the legs as seen in Figure 51.

Correct calibration procedures and regular cleaning of the sensors is therefore vital to optimal system operation. Correct calibration procedures will dramatically reduce the error experienced by the sensor measurements. Regular cleaning will also keep the components clean resulting in better measurements.

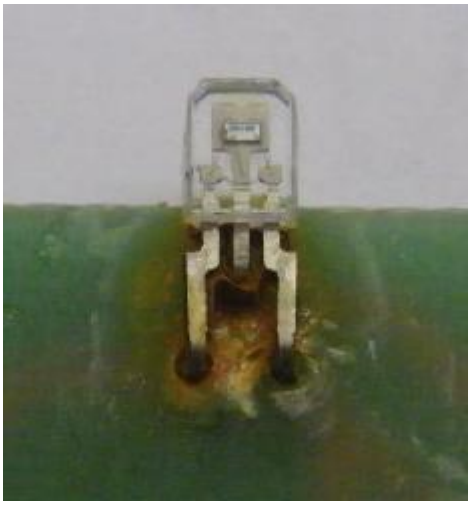

Figure 51: Sensor Degradation

8 PROTOTYPE EVALUATION

Through careful analysis and scrutiny of the testing procedure and the results obtained and documented in section 7, it can be determined that the prototype system was a success under the circumstances for which it was specifically developed.

The system prototype is able to fully describe the variability of light, within the testing area, in both the spatial and time domains. This can be clearly seen in the progression on light documented in Figure 46 to Figure 50 The system achieved this through simultaneous measurement, at multiple locations by sensors with spectral sensitivity similar to that of the human eye. The measured data was then processed and used to generate the easy to interpret graphics showing the illumination characteristics within the area. Successive, time-stamped data recordings can be used to generate sequential imaging showing how the light within the area changes with respect to time.

During development of the system a number of both positive and negative aspects of the design came to light.

8.1 Prototype Strengths

Through the careful selection and design of the sensor the system was able to accurately measure ambient light levels between 100 lux and 1000 lux in the visible spectrum seen by the human eye.

The sensor measurements proved to be well within the design requirement of 20% accuracy with errors from the Sharp sensor not exceeding 10% during sensor development.

The prototype proved that an area of 2m x 2m in size could easily be covered with the only limit to the system size being the length of the connector cables.

The recorded data can be easily and quickly viewed as text from the removable SD card.

Data measurements are taken at all locations in a matter of milliseconds with the only delays being the multiplexer switching and the ADC conversion. This is much faster than single hand held measurements taken at each location. In terms of the project it can therefore considered simultaneous.

The number of sensors and the time interval between measurements can be easily altered by changing a single value for each system characteristic in the system code. This allows for easy customisability of the system to meet requirements. Sensors themselves can also be easily replaced in the event of failure.

The system proved to be far more inexpensive than commercially available systems that could perform similar functions.

8.2 Prototype Weaknesses

The prototype, as it is, does not have any protection in the form of a protective housing or protective covering leaving it vulnerable to damage and degradation. This results in sensors losing accuracy if regular calibration procedures and sensor cleaning is not implemented. In addition, it is not waterproof so it runs the risk of damage and malfunction in the event of water getting onto the system.

The large volume of cabling can prove cumbersome at times but this can be reduced with careful planning if the measurement location is known. The large volume of cabling also makes setting up the system a slow process as well as making system storage a problem. Careful planning can be done to use shorter cables that are just long enough to reach each sensor location from the central node, minimising the influence of the cabling where possible.

Ensuring that each sensor is level with an unobstructed view upwards proved difficult. Any cabling movement resulted in sensor movement and each sensor had to therefore be secured in place with adhesive tape. A sensor housing with built in levelling or a means to secure a sensor in place could prove beneficial.

9 POTENTIAL SYSTEM USES

The system was initially designed to meet the requirements of a single problem encountered during the design, installation and testing of a daylighting system for a rural South African classroom.

The success of the prototype under the desired conditions shows that the system could be useful in aiding the development of daylighting systems in general not just specifically for applications in rural classrooms. This could be accomplished due to the ability of the system to monitor and record the variations in illumination levels on an hourly, daily or even seasonal basis in order to fully describe the performance of the specific daylighting application.

The designed system could also have other uses or implementations where it could prove effective. A short summary of possible applications is highlighted below:

- The development of dynamic metrics to model the expected distribution of lighting can potentially be aided by use of a system such as this. The system can measure actual results which can be compared to the modelled data; thereby verifying the dynamic metrics model or helping to improve the model. This will in turn benefit green architecture applications where dynamic metrics can be utilised.
- The system can also be utilised in various environments such as office space, schools, medical facilities, mines and numerous others to ensure that the illumination within these areas meets the SABS standards set out.
- The system can be adapted slightly and incorporated into intelligent lighting control systems for various purposes.
- The system could also prove to be useful in areas of agriculture. In controlled environment agriculture, for example, light measurements are taken to indicate the possible amount of photosynthesis and growth performed by the plant (Brechner & Both n.d.). Lux meters designed to match the sensitivity over the human eye tend to overestimate, by about 25%, the amount of light available for photosynthesis. The system could however be adapted to fit the requirements by using quantum sensors with the capability of measuring Photosynthetically Active Radiation (PAR) in place of the standard lux meters.
- Another example of a potential application could be in the canopy management of vineyards. Light intensity is the main driver of photosynthesis and is therefore the most important factor for ripening of fruit (Andras 2006). The system can therefore be used to determine light levels passing through the canopy giving the viticulturist vital information.
- These agricultural implementations could be expanded to include citrus orchards, hydroponic installations, poultry, environmentally sensitive vegetables and many more.

10 CONCLUDING REMARKS

The primary aim of the project was to design, develop and test a system able to measure, record and convey the variability of light within an area. This was to be done in both the spatial and time domains, with respect to the working area of a light pipe installation designed for use in rural South African classrooms. The measurement system had to be much more cost effective than similar commercially available systems.

Artificial lighting is responsible for some 20% of electrical energy usage globally. Daylighting systems have the potential to reduce this figure dramatically with wide ranging environmental and social benefits. They also have the potential to bring light to rural areas previously without lighting. These systems have however, been poorly received to date due to high prices and imperfect performance of the technologies. The primary goal was therefore to aid the implementation, advancement and improvement of daylighting systems.

With the use of the developed measurement system, daylighting systems can be tested, analysed and improved with the data obtained, for a dramatically reduced cost compared with commercially available products.

The initial literature review conducted provided a thorough understanding of what the system was required to measure. The properties of light, quality of light, the process of daylighting and current technologies and methods associated with light measurement were all investigated. The literature review assisted the creation of system requirements, narrowing the search for components through the understanding of what would be required from the measurement devices.

A stringent component screening and selection process was undertaken in order to identify those which had detection characteristics similar to the human eye and that would meet the system requirements. The identified components underwent rigorous testing and calibration procedures to determine the most appropriate component for system. The Sharp GA1A2S100LY sensing device proved to be the most suitable and was further developed to accurately measure up to 1500 lux. The sensor was then included in a microcontroller based system to record illumination levels at multiple locations simultaneously.

The prototype system that was subsequently developed proved to be a success under the circumstances for which it was developed. The use of 16 sensors in the system design proved unable to accurately track the variability of light within the testing area, however, the improved 64 sensor design proved capable of accurately tracking the light variations. This can be seen through careful analysis and scrutiny of the system development as well as the results obtained.

The completed system is able to successfully measure, record and represent the variability of light within the testing area, fully describing it in the spatial and time domains. The system achieves this by simultaneous measurement, at multiple

locations, by sensors with spectral sensitivity similar to that of the human eye. The measured data is then stored on an SD card. The data is then processed using Matlab software to generate the easy to interpret graphics showing the illumination characteristics within the area.

The search for commercially available systems capable of fully describing the variations of light generated through daylighting systems proved disappointing. Available options were exceedingly expensive and seemed inadequate. The prototype system developed in this project, for just R6 216.09, is a fraction of the cost of the similar, commercially available systems that were quoted in excess of R350 000.00.

The prototype system developed through the project meets each of the initial design requirements set for the project. This leads to the conclusions that the project, within the specific design requirements, was a success. The system will be able to aid the design, installation and testing of a daylighting system for a rural South African classroom. This is done by being able to monitor and record the variations in illumination levels on an hourly, daily or even seasonal basis to fully describe the performance of the daylighting system being used.

This project was able to identify alternative potential uses for the developed system; branching away from the single application within South African rural classrooms. Therefore the system has numerous other potential uses that can be further investigated.

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APPENDIX A: DATA SHEET EXTRACTS

A.1 Illuminance Sensor Data Sheet Extracts

SHARP

GA1A2S100SS/GA1A2S100LY

GA1A2S100SS/ GA1A2S100LY

OPIC™ Linear Output Ambient Light Sensor

■ Features

1. Linear output, suitable for indoor or outdoor use
2. Light sensitivity and response curve similar to that of the human eye
3. OPIC light detector: integrated photodiode and signal processing circuit
4. Lead frame packages:
   Straight leads: GA1A2S100SS
   L-bend: GA1A2S100LY
5. Stable over specified temperature range
6. Lead-free and RoHS-directive compliant

■ Agency Approvals/Compliance

1. Compliant with RoHS directive (2002/95/EC)
2. Content information about the six substances specified in "Management Methods for Control of Pollution Caused by Electronic Information Products Regulation" (popular name: China RoHS) (Chinese: 电子信息产品污染控制管理办法); refer to page 7.

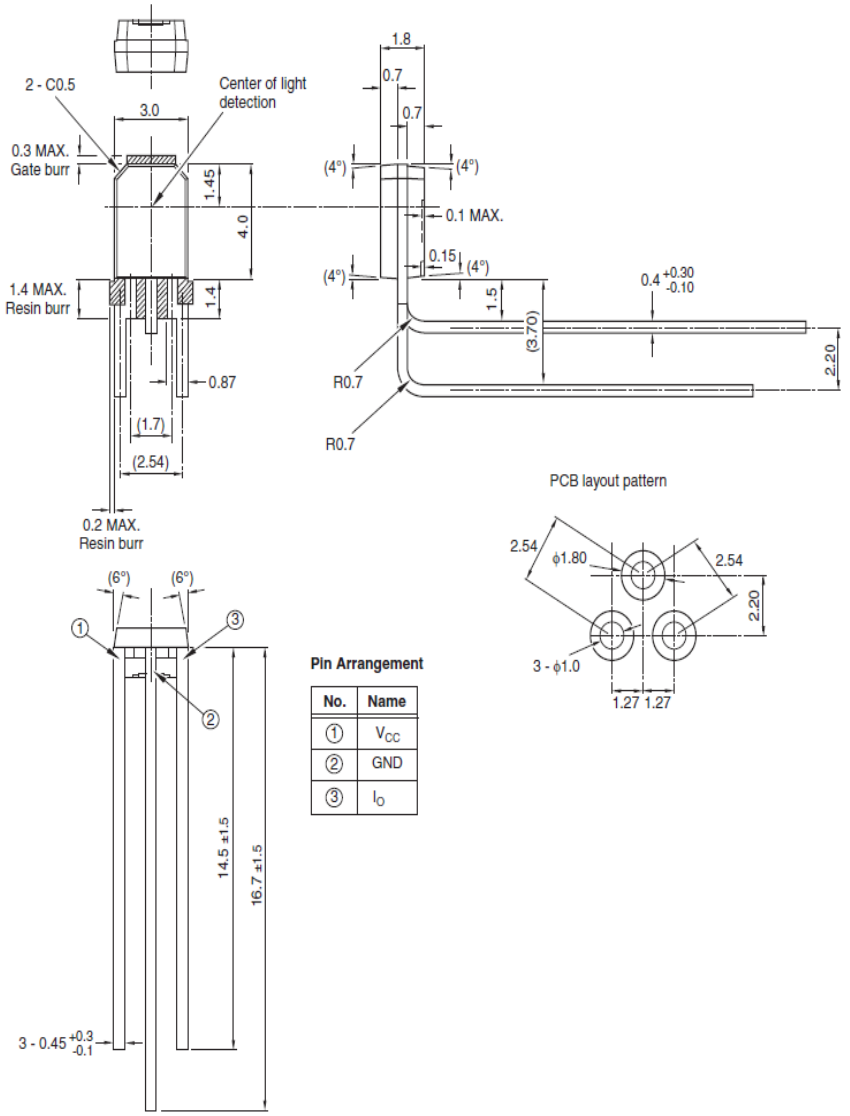
■ Applications

1. Auto-dimming circuits
2. Office automation equipment
3. Audio visual equipment
4. Home appliances
5. Touch panels

OPIC is a trademark of Sharp Corporation.

Sheet No.: D1-A00601EN
Date: October 1, 2007

GA1A2S100LY



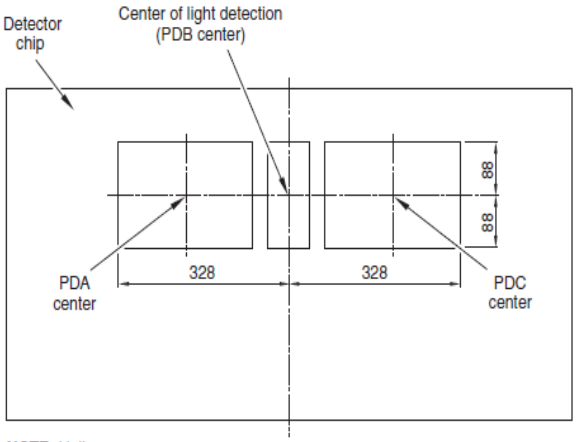
Pin Arrangement

No.	Name
①	V_{CC}
②	GND
③	I_O

NOTES:

1. Units: mm
2. Unspecified tolerance: ±0.2 mm
3. ( ): Reference dimensions
4. Package: Transparent
5. Burr thickness (0.05 mm MAX.) and gate burr thickness (0.3 mm MAX.) are not included in the outline dimensions.
6. Resin protrusion: 1.4 mm MAX. however, the thin burr adheres to the lead 1.4 mm MAX. from the resin.

■ Detector Shape



NOTE: Unit: µm

■ Absolute Maximum Ratings

(Ta = 25°C)

Parameter	Symbol	Rating	Unit
Supply voltage	V_{CC}	-0.3 to +7.0	V
Output current	I_O	5	mA
Operating temperature	Topr	-40 to +85	°C
Storage temperature	Tstg	-40 to +85	°C
Soldering temperature *1	Tsol	260	°C

*1 Within 5 s (MAX.), no closer than 1.4 mm from edge.

■ Recommended Operating Conditions

(Ta = 0°C to 70°C)

Parameter	Symbol	MIN.	MAX.	Unit
Operating Supply Voltage	V_{CC}	2.7	3.6	V
Output Voltage	V_{OUT}	0	V_{CC} – 1.0	V
Illuminance Range	E_V	10	10000	lx

APDS-9005

Miniature Surface-Mount Ambient Light Photo Sensor

AVAGO TECHNOLOGIES

Data Sheet

Description

The APDS-9005 is a low cost analog-output ambient light photo sensor in miniature chipLED lead-free surface mount package. It consists of a photo sensor, whose spectral response is close to the CIE standard photopic observer, as show in figure 2. The APDS-9005 is ideal for applications in which the measurement of ambient light is used to control display backlighting. Mobile appliances such as the mobile phones and PDAs that draw heavy current from display backlighting will benefit from incorporating these photo sensor products in their designs by reducing power consumption significantly.

Application Support Information

The Application Engineering Group is available to assist you with the application design associated with APDS-9005 ambient light photo sensor module. You can contact them through your local sales representatives for additional details.

Features

- Spectral responsivity close to that of human eye
- Miniature ChipLED Leadfree surface-mount package
  - Height – 0.55 mm
  - Width – 1.60 mm
  - Depth – 1.50 mm
- Low sensitivity variation across various light sources
- Recommended operating temperature : -40°C to 85°C
- Vcc supply 1.8 to 5.5V
- Lead-free package, RoHS compliance
- Output linearity across wide illumination range

Applications

- Detection of ambient light to control display backlighting
  - Mobile devices – Mobile phones, PDAs
  - Computing devices – Notebooks, Webpads
  - Consumer devices – TVs, Video Cameras, Digital Still Camera
- Automatic Residential and Commercial Lighting Management
- Electronic Signs and Signals

Ordering Information

Part Number	Packaging Type	Package	Quantity
APDS-9005-020	Tape and Reel	6-pins Chipled package	2500

Typical Application Circuit

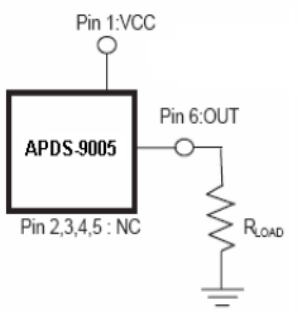


Figure 1. Typical application circuit for APDS-9005

Component	Recommended Application Circuit Component
RLOAD	1k ohm

Note :
Refer to Figure 11 for General Luminance Vs Typical Output Voltage for different RLOAD values

I/O Pins Configuration Table

Pin	Symbol	Description
1	VCC	VCC
2	NC	No Connect
3	NC	No Connect
4	Nc	No Connect
5	NC	No Connect
6	Iout	Out

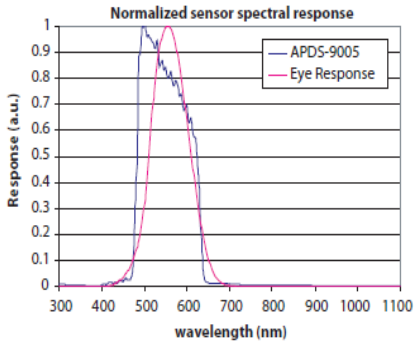


Figure 2. Relative Spectral Response Vs Wavelength

CAUTIONS : It is advised that normal static precautions be taken in handling and assembly of this component to prevent damage and/or degradation which may be induced by ESD

Absolute Maximum Ratings

For implementations where case to ambient thermal resistance is ≤ 50 °C /W

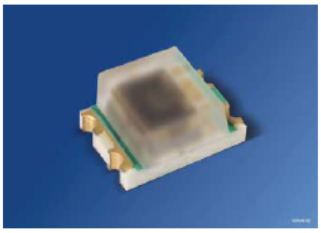
Parameter	Symbol	Min.	Max.	Units
Storage Temperature	T_S	-40	85	°C
Operating temperature	T_A	-40	85	°C
Supply Voltage	V_{CC}	0	6	V

Recommended Operating Conditions

Parameter	Symbol	Min.	Max.	Units	Conditions
Supply Voltage	V_{CC}	1.8	5.5	V	

Hochgenauer Umgebungslichtsensor
High Accuracy Ambient Light Sensor
Lead (Pb) Free Product - RoHS Compliant

SFH 5711



Wesentliche Merkmale

- Optohybrid mit logarithmischem Stromausgang
- Perfekt an die Augenempfindlichkeit (Vλ) angepasst
- Niedriger Temperaturkoeffizient der Fotoempfindlichkeit
- Hohe Genauigkeit über weiten Beleuchtungsstärkebereich
- Automotive Freigabe

Features

- Opto hybrid with logarithmic current output
- Perfect match to Human Eye Sensitivity (Vλ)
- Low temperature coefficient of spectral sensitivity
- High accuracy over wide illumination range
- Automotive qualified

Anwendungen

- Anwendungen im Automobilbereich
- Sonnenlichtsensor / Fahrlichtkontrolle
- Steuerung von Displayhinterleuchtungen
- Mobile Geräte

Applications

- Automotive applications
- Sunlight sensor / head lamp control
- Control of display backlighting
- Mobile devices

Typ Type	Bestellnummer Ordering Code	**Ausgangsstrom**, E_v= 1000lx, (white LED LW 541C) **Output current**, I_{OUT} / µA
SFH 5711-2/3[1)]	Q65110A4513	27 - 32
SFH 5711-1/2[1)]	on request	25 - 30
SFH 5711-3/4[1)]	on request	29 - 34

[1)] Nur eine Gruppe innerhalb einer Verpackungseinheit, siehe Kenndaten.
Only one bin within one packing unit, see characteristics

Grenzwerte
Maximum Ratings

Bezeichnung Parameter	Symbol Symbol	Wert Value	Einheit Unit
Betriebs- und Lagertemperatur Operating ans storage temperature range	T_{stg}	– 40 ... + 100[1)]	°C
Versorgungsspannung Supply Voltage	V_{DD}	6	V
Ausgangsspannung Output voltage	V_{OUT}	$< V_{DD}$	V
Elektrostatische Entladung Electrostatic Discharge Human Body Model according to EOS/ESD-5.1-1993	ESD	2	kV

[1)] JEDEC level 4

Empfohlener Arbeitsbereich
Recommended Operating Conditions

Bezeichnung Parameter	Symbol Symbol	Wert Value			Einheit Unit
		min.	typ.	max.	
Betriebsspannung Supply Voltage	V_{DD}	2.3		5.5	V
Beleuchtungsstärke Illuminance T_A = – 30 °C ... + 70 °C T_A = – 40 °C ... + 100 °C	E_V		 3 ... 80k 10...80k		lx

Kennwerte (T_A = 25 °C)
Characteristics

Bezeichnung Parameter	Symbol Symbol	Wert Value			Einheit Unit
		min.	typ.	max.	
Stromaufnahme, E_V = 0 Current consumption V_{DD} = 2.5 V V_{DD} = 5.0 V	I_{DD}		 410 420	 500	µA
Stromaufnahme, E_V = 1000lx Current consumption, E_V = 1000lx V_{DD} = 2.5 V V_{DD} = 5.0 V	I_{DD}		 460 470	 550	µA
Spektraler Bereich der Fotoempfindlichkeit Spectral range of sensitivity	$\lambda_{10\%}$		475 ... 650		nm
Wellenlänge der max. Fotoempfindlichkeit Wavelength of max. photosensitivity	$\lambda_{s\,max}$	540	555	570	nm
Abmessung der bestrahlungsempfindlichen Fläche Dimensions of radiant sensitive area	$L \times B$ $L \times W$		0.4 x 0.4		mm x mm
Ausgangskapazität Output capacitance	C_{OUT}		3		pF
Transferfunktion Transfer function, s. Fig. 1	G	9.5	10	10.5	µA / dek µA / dec
Abweichung der Ausgangskennlinie von der Logarithmierfunktion Deviation of Outputcharacteristic from logarithmic function, s. Fig. 1	L	- 3		+ 3	%
Maximale Ausgangsspannung Maximum output voltage	V_{OUT}			V_{DD} - 0.5	V
Einschaltzeit, E_V = 1000 lx Power on time, E_V = 1000 lx V_{DD} = 0V -> V_{DD}	t_{ON}		 0.1	 1.2	ms
Antwortzeit, R_L = 25 kOhm, C = 1 nF Response Time, s. Fig. 2 E_V = 100 -> 1000 lx E_V = 1000 -> 100 lx	t_r / t_f		 0.03 0.1		ms

Kennwerte (T_A = 25 °C)
Characteristics

Bezeichnung Parameter	Symbol Symbol	Wert Value			Einheit Unit
		min.	typ.	max.	
Ausgangsgenauigkeit über Temperaturbereich[1)] Output Accuracy Over Temperature Range[1)] E_V = 1000 lx T_A = – 40 °C ... + 100 °C T_A = – 30 °C ... + 70 °C T_A = 0 °C ... + 50 °C	ΔI_{OUT}	 –2.0 –1.5 –0.7	 ±1.0 ±0.6 ±0.2	 +2.0 +1.5 +0.7	µA
Ausgangsdunkelstrom, E_V = 0 Output dark current	I_{out}		0.1	100	nA

[1)] Diese Werte entsprechen einer Photodiode mit einem TC von ungefähr 0.3 %/K.
These values correspond to a photodiode with a TC of approximately 0.3 %/K.

Guppierung (T_A = 25 °C)
Binning

Bezeichnung Parameter	Symbol Symbol	Wert Value				Einheit Unit
		-1	-2	-3	-4	
Ausgangsstrom[1)] Output current E_V = 1000lx (white LED LW 541C)	I_{out}	25 ... 28	27 ... 30	29 ... 32	31 ... 34	µA

[1)] 3µA Gruppenbreite entspricht einem Verhältnis von 1:2 in der Bestrahlungsstärke.
3µA bin width is equivalent to a spread of 1:2 of the irradiance.

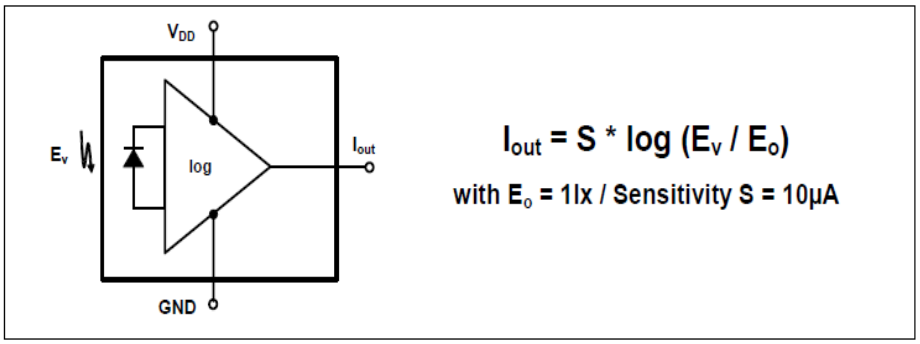


Figure 1 **Ersatzschaltbild**
Circuitry

A.2 Shuttle SDIM-T-LED-500W Dimmer Module Data Sheet

Shuttle

SDIM-T-LED-500W

ELECTRICAL SPECIFICATIONS

Normal Operating Voltage	*190-253VAC, 50Hz ±5%*
Dimming Method	*Trailing Edge*
Minimum Operating Voltage	*100VAC*
Max. Wire Resistance (bell-press control)	*50kΩ*
Minimum Load Power	
• **Resistive**	*2W*
• **Inductive**	*Not Compatible*
• **Electronic Transformer**	*20W*
Maximum Load Power	*See table below*
Retain Memory After Power Failure	*Yes*
Brown-Out Protection	*Yes*
High Frequency AC transient protection	*Yes*
Surge Protection	*Yes, 400mJ*

LOAD COMPATIBILITY AND MAXIMUM RATINGS

230VAC, Resistive & Electronic low voltage	Dimmable LED 230VAC & 12V	Wire Wound & Inductive Loads	Fluorescent & CFL
500VA (240VAC) 2.1A max	500VA (240VAC) 2.1A max	NOT Compatible	NOT Compatible

SOFTWARE FEATURES

Microprocessor Control	*Yes*
Soft Start and Soft Off	*Yes*
Bell-press Control	*Continuous cycling*
Minimum Intensity Control	*Yes*
Memory	*Yes, returns to previous dimming level when turned on*

ENVIRONMENTAL

Operating Temperature	*-5 - +45°C*
Storage Temperature	*-30 - +80°C*
Maximum Housing Temperature	*85°C*
Relative Humidity	*90% (non condensing)*
Enclosure	*42 x 42 x 12mm Black Aluminium*

CONFORMITY

EMC	*SANS 215, CISPR 15:2009* *SABS CISPR 22:2008*
Safety	*IEC 60669-1:2007, SANS 60669-1: 2007* *IEC 60669-2-1:2009, SANS 60669-2-1:2009*
SABS/NRCS Approval	*RCC no 1206515*

January 2013

A.3 SDL400 Light Meter Data Sheet

EXTECH® INSTRUMENTS

Experience the Extech Advantage

PRODUCT DATASHEET

Light Meter/Datalogger

Records data on an SD card in Excel® format

For easy transfer to a PC for analysis

Features:

- Wide range to 10,000Fc or 100kLux
- Cosine and color-corrected measurements
- Utilizes precision silicon photo diode and spectral response filter
- Datalogger date/time stamps and stores readings on an SD card in Excel® format for easy transfer to a PC
- Offset adjustment used for zero function to make relative measurements
- Adjustable data sampling rate: 1 to 3600 seconds
- Stores 99 readings manually and 20M readings via 2G SD card
- Type K/J Thermocouple input for high temperature measurements
- Large backlit LCD display
- Record/Recall MIN, MAX readings
- Data Hold plus Auto power off with disable function
- Built-in PC interface
- Complete with 6 x AA batteries, SD card, hard carrying case and light sensor with 45" (1.1m) cable and protective cover

Measures a wide range of light conditions

Specifications	Range	Resolution	Basic Accuracy
Fc Range	200, 2000, 10kFc	0.1Fc	±4%rdg
Lux Range	2000, 20k, 100kLux	1Lux	±4%rdg
Type K Temperature	-148 to 2372°F (-100 to 1300°C)	0.1°	±(0.4% + 1.8°F/1°C)
Type J Temperature	-148 to 2192°F (-100 to 1200°C)	0.1°	±(0.4% + 1.8°F/1°C)
Memory	20M data records using 2G SD card		
Dimensions	7.2 x 2.9 x 1.9" (182 x 73 x 47.5mm)		
Weight	16.2oz (475g)		

Ordering Information:

SDL400 .....Light Meter/Datalogger
SDL400-NIST .....SDL400 w/Certificate of Calibration Traceable to NIST standards

872502 .....Type J Bead Wire Probe (-328 to 392°F/-200 to 200°C)
TP870 .....Type K Bead Wire Probe (-40 to 482°F/-40 to 250°C)
TP200 .....Type K Clamp Probe (-4 to 200°F/-20 to 93°F)
TP400 .....Type K Clamp Probe (-4 to 450°F/-20 to 232°C)
153117 .....117V AC Adaptor
UA100-240 .....100-240V AC Adaptor with 4 plugs (US, EU, UK, AU)

CE 3 WARRANTY YEARS

www.extech.com

Specifications subject to change without notice.

10/30/13 - R1

A.4 Extract From the OSRAM LED SUPERSTAR PAR16 50 36° Advanced lamp

LED SUPERSTAR PAR16 50 36° ADVANCED 恒亮LED PAR16射灯 7.5 W	
W	7.5 W
· cd · lm	36° · 1000 cd · 400 lm
T[Kelvin]	6500 K = daylight, 日光色
Ra	80
	0 s = 100% light, 瞬时启动
	Dimmable, 可调光
t[h]*	25000 h, 小时
	100000
Hg	0.0 mg
V · Hz	220-240 V · 50/60 Hz
	GU10

A.5 Extract From MCP9700A Thermistor Data Sheet

MICROCHIP

MCP9700/9700A
MCP9701/9701A

Low-Power Linear Active Thermistor™ ICs

Features

- Tiny Analog Temperature Sensor
- Available Packages:
  - SC70-5, SOT-23-5, TO-92-3
- Wide Temperature Measurement Range:
  - -40°C to +125°C (Extended Temperature)
  - -40°C to +150°C (High Temperature) **(MCP9700/9700A)**
- Accuracy:
  - ±2°C (max.), 0°C to +70°C (**MCP9700A/9701A**)
  - ±4°C (max.), 0°C to +70°C (**MCP9700/9701**)
- Optimized for Analog-to-Digital Converters (ADCs):
  - 10.0 mV/°C (typical) **MCP9700/9700A**
  - 19.5 mV/°C (typical) **MCP9701/9701A**
- Wide Operating Voltage Range:
  - V_{DD} = 2.3V to 5.5V **MCP9700/9700A**
  - V_{DD} = 3.1V to 5.5V **MCP9701/9701A**
- Low Operating Current: 6 µA (typical)
- Optimized to Drive Large Capacitive Loads

Typical Applications

- Hard Disk Drives and Other PC Peripherals
- Entertainment Systems
- Home Appliance
- Office Equipment
- Battery Packs and Portable Equipment
- General Purpose Temperature Monitoring

Description

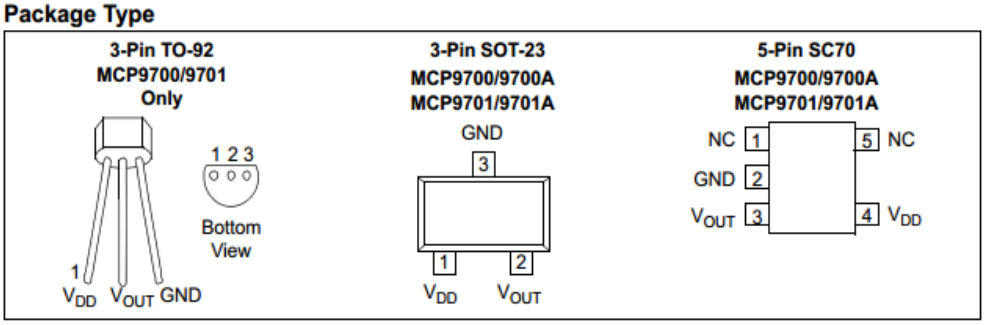
The MCP9700/9700A and MCP9701/9701A family of Linear Active Thermistor™ Intergrated Circuit (IC) is an analog temperature sensor that converts temperature to analog voltage. It's a low-cost, low-power sensor with an accuracy of ±2°C from 0°C to +70°C (MCP9700A/9701A) ±4°C from 0°C to +70°C (MCP9700/9701) while consuming 6 µA (typical) of operating current.

Unlike resistive sensors (such as thermistors), the Linear Active Thermistor IC does not require an additional signal-conditioning circuit. Therefore, the biasing circuit development overhead for thermistor solutions can be avoided by implementing this low-cost device. The voltage output pin (V_{OUT}) can be directly connected to the ADC input of a microcontroller. The MCP9700/9700A and MCP9701/9701A temperature coefficients are scaled to provide a 1°C/bit resolution for an 8-bit ADC with a reference voltage of 2.5V and 5V, respectively.

The MCP9700/9700A and MCP9701/9701A provide a low-cost solution for applications that require measurement of a relative change of temperature. When measuring relative change in temperature from +25°C, an accuracy of ±1°C (typical) can be realized from 0°C to +70°C. This accuracy can also be achieved by applying system calibration at +25°C.

In addition, this family is immune to the effects of parasitic capacitance and can drive large capacitive loads. This provides Printed Circuit Board (PCB) layout design flexibility by enabling the device to be remotely located from the microcontroller. Adding some capacitance at the output also helps the output transient response by reducing overshoots or undershoots. However, capacitive load is not required for sensor output stability.

Package Type

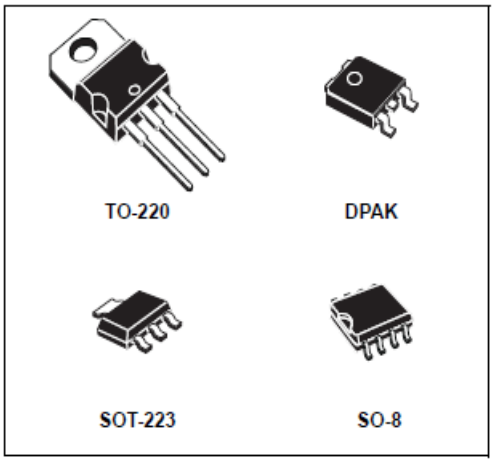


A.6 Extract From LD1117-TO-220 Regulator Data Sheet

LD1117 SERIES

LOW DROP FIXED AND ADJUSTABLE POSITIVE VOLTAGE REGULATORS

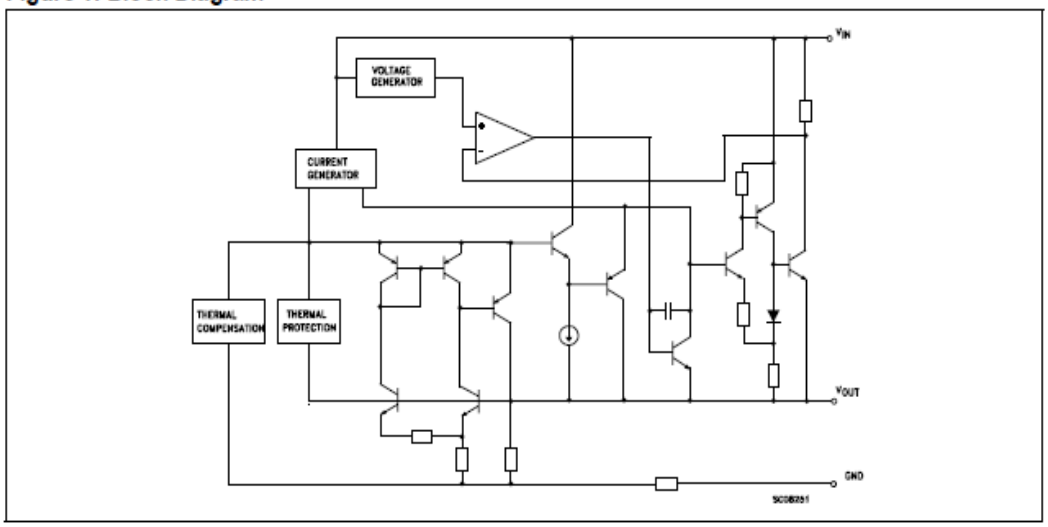
- LOW DROPOUT VOLTAGE (1V TYP.)
- 2.85V DEVICE PERFORMANCES ARE SUITABLE FOR SCSI-2 ACTIVE TERMINATION
- OUTPUT CURRENT UP TO 800 mA
- FIXED OUTPUT VOLTAGE OF: 1.2V, 1.8V, 2.5V, 2.85V, 3.0V, 3.3V, 5.0V
- ADJUSTABLE VERSION AVAILABILITY (V_{rel}=1.25V)
- INTERNAL CURRENT AND THERMAL LIMIT
- AVAILABLE IN ± 1% (AT 25°C) AND 2% IN FULL TEMPERATURE RANGE
- SUPPLY VOLTAGE REJECTION: 75dB (TYP.)



DESCRIPTION

The LD1117 is a LOW DROP Voltage Regulator able to provide up to 800mA of Output Current, available even in adjustable version (Vref=1.25V). Concerning fixed versions, are offered the following Output Voltages: 1.2V,1.8V,2.5V,2.85V, 3.0V 3.3V and 5.0V. The 2.85V type is ideal for SCSI-2 lines active termination. The device is supplied in: SOT-223, DPAK, SO-8 and TO-220. The SOT-223 and DPAK surface mount packages optimize the thermal characteristics even offering a relevant space saving effect. High efficiency is assured by NPN pass transistor. In fact in this case, unlike than PNP one, the Quiescent Current flows mostly into the load. Only a very common 10µF minimum capacitor is needed for stability. On chip trimming allows the regulator to reach a very tight output voltage tolerance, within ± 1% at 25°C. The ADJUSTABLE LD1117 is pin to pin compatible with the other standard. Adjustable voltage regulators maintaining the better performances in terms of Drop and Tolerance.

Figure 1: Block Diagram



A.7 Extract From CD74HC4067 Multiplexer Data Sheet

TEXAS INSTRUMENTS

Data sheet acquired from Harris Semiconductor
SCHS209C

February 1998 - Revised July 2003

CD74HC4067, CD74HCT4067

High-Speed CMOS Logic
16-Channel Analog Multiplexer/Demultiplexer

Features

- Wide Analog Input Voltage Range
- Low "ON" Resistance
  - V_{CC} = 4.5V. . . . . 70Ω (Typ)
  - V_{CC} = 6V . . . . . 60Ω (Typ)
- Fast Switching and Propagation Speeds
- "Break-Before-Make" Switching. . . . . 6ns (Typ) at 4.5V
- Available in Both Narrow and Wide-Body Plastic Packages
- Fanout (Over Temperature Range)
  - Standard Outputs . . . . . 10 LSTTL Loads
  - Bus Driver Outputs . . . . . 15 LSTTL Loads
- Wide Operating Temperature Range . . . -55°C to 125°C
- Balanced Propagation Delay and Transition Times
- Significant Power Reduction Compared to LSTTL Logic ICs
- HC Types
  - 2V to 6V Operation
  - High Noise Immunity: N_{IL} = 30%, N_{IH} = 30% of V_{CC} at V_{CC} = 5V
- HCT Types
  - 4.5V to 5.5V Operation
  - Direct LSTTL Input Logic Compatibility, V_{IL} = 0.8V (Max), V_{IH} = 2V (Min)
  - CMOS Input Compatibility, $I_I \leq 1\mu A$ at V_{OL}, V_{OH}

Description

The CD74HC4067 and CD74HCT4067 devices are digitally controlled analog switches that utilize silicon-gate CMOS technology to achieve operating speeds similar to LSTTL, with the low power consumption of standard CMOS integrated circuits.

These analog multiplexers/demultiplexers control analog voltages that may vary across the voltage supply range. They are bidirectional switches thus allowing any analog input to be used as an output and vice-versa. The switches have low "on" resistance and low "off" leakages. In addition, these devices have an enable control which when high will disable all switches to their "off" state.

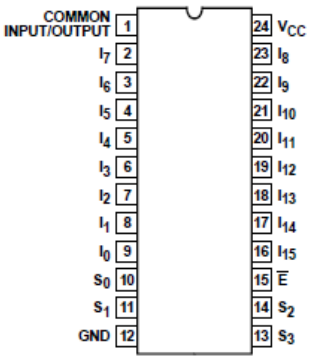
Ordering Information

PART NUMBER	TEMP. RANGE (°C)	PACKAGE
CD74HC4067E	-55 to 125	24 Ld PDIP
CD74HC4067M	-55 to 125	24 Ld SOIC
CD74HC4067M96	-55 to 125	24 Ld SOIC
CD74HC4067SM96	-55 to 125	24 Ld SSOP
CD74HCT4067M	-55 to 125	24 Ld SOIC

NOTE: When ordering, use the entire part number. The suffix 96 denotes tape and reel.

Pinout

CD74HC4067 (PDIP, SOIC, SSOP)
CD74HCT4067 (SOIC)
TOP VIEW



CAUTION: These devices are sensitive to electrostatic discharge. Users should follow proper IC Handling Procedures.

1

APPENDIX B: C CODE

B.1 Sample Code for Concept Design and Sensor Development

```
/*
 * File:   APDS 9005 Sensor Testing.c
 * Author: Kevin Smith
 *
 * 2014
 *
 * This program is used to test the APDS9005 illuminance sensor.
 * Sensors outputs are relayed to the PIC18 where the value is converted and
 * displayed on the LCD for easy viewing
 *
 */

#include <p18f8722.h>
#include <spi.h>
#include <delays.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <adc.h>

#define sample ADCON0bits.GO_DONE
#define CS PORTAbits.RA2

#define IODIRA_ADDRESS 0x00
#define IODIRB_ADDRESS 0x01
#define GPIOA_ADDRESS  0x12
#define GPIOB_ADDRESS  0x13

#pragma config OSC = HS
#pragma config WDT = OFF

//Method prototypes.
void setIODIR(char, char);
void setGPIO(char, char);
void lcdCommand(char);
void lcdChar(unsigned char);
void lcdGoTo(char);
void lcdWriteMessage(rom unsigned char *str);
void lcdWriteVariable(char *str);
void startRead(unsigned char channel);
void floatToChar(char *str, double num);

void main(void)
{
    char str[8] = ""; //Hold string value of floats for writing to LCD.
    double x=0.0; //Holds value of AD conversion.
    double y=0.0;
    int i =0;
    TRISA = 0xFF;
    Delay10TCYx(5);      // Delay for 50TCY
    PORTA = 0x00;
    Delay10TCYx(5);      // Delay for 50TCY
    TRISAbits.RA2=0; // our chip select pin needs to be an output so that we can
toggle it
    CS=1; // set CS pin to high, meaning we are sending any information to the
MCP23S17 chip

    // configure SPI: the MCP23S17 chip's max frequency is 10MHz, let's use
10MHz/64 (Note FOSC=10Mhz, our external oscillator)
    OpenSPI1(SPI_FOSC_64, MODE_10, SMPEND); // frequency, master-slave mode,
sampling type
    // set LCD pins DB0-DB7 as outputs
    setIODIR(IODIRB_ADDRESS,0x00);
    // set RS and E LCD pins as outputs
    setIODIR(IODIRA_ADDRESS,0x00);
    // RS=0, E=0
```

```
    setGPIO(IODIRA_ADDRESS,0x00);
    // Function set: 8 bit, 2 lines, 5x8
    lcdCommand(0b00111111);
    // Cursor or Display Shift
    lcdCommand(0b00001111);
    // clear display
    lcdCommand(0b00000001);
    // entry mode
    lcdCommand(0b00000110);

    TRISAbits.RA0 = 1; //Sets pin to AN0 function. (Pot)
    TRISFbits.RF1 = 1; //Sets pin to AN1 function. (External temp)
    Delay10TCYx(5);      // Delay for 50TCY
    TRISD = 0x00;
    PORTD = 0x01;
    MEMCONbits.EBDIS = 1;
    ADCON1 = 0b00000000; //Sets voltage references and configures ports as A/D.
    ADCON0 = 0b00000001; //Selects channel and used to start AD conversions.
    /*
     * Select Conversion clock and acquisition time.
     * Selected Fosc/64 and 4 TAD to stop intereference between components
     * on different ADC channels. (I.e. pot and on-board temp sensor) This
     * is because they share the same 5V supply line.
     */
    ADCON2 = 0b10111110;

    Delay10TCYx(5);      // Delay for 50TCY
    //Write message headings to LCD.
    lcdWriteMessage("Volt:");
    lcdGoTo(0x40);
    lcdWriteMessage("Lux1:");
    while(1)
    {
         startRead(0);
         lcdGoTo(0x05);
         x = ReadADC();
         x = x*(3.3/1023.0); // Read result
         floatToChar(str, x);
         lcdWriteVariable(str);

         Delay10TCYx(1);

         startRead(6);
         lcdGoTo(0x45);
         x=0.0;
         for(i=0; i<100;i++)
         {
             x = ReadADC();
             Delay10TCYx(1);
             x = (x*(3.3/1023.0))*1000; // Read result
             y+= x;
         }
         y/=100.0;
         floatToChar(str, y);
         lcdWriteVariable(str);
    }
    return;
}

/*
 * used to set the values of the ports ( think of it as when you use a PORT
register)
 */
void setGPIO(char address, char value){
    CS=0; // we are about to initiate transmission
    // pins A2,A1 and A0 of the MCP23S17 chip are equal to 0 because they are
grounded
    // we are just going to be writing so R/W=0 also
    WriteSPI1(0x40);    // write command 0b0100[A2][A1][A0][R/W] = 0b01000000 =
0x40
    WriteSPI1(address); // select register by providing address
```

```
    WriteSPI1(value);    // set value
    CS=1; // we are ending the transmission
}

/*
 * used to set the directions of the ports (like when you use TRIS registers)
 * this function is actually identical to setGPIO, but I think a different
function
 * for setting the port direction helps with keeping the code organized
 */
void setIODIR(char address, char dir){
    CS=0;
    WriteSPI1(0x40);    // write command (0b0100[A2][A1][A0][R/W]) also equal to
0x40
    WriteSPI1(address); // select IODIRB
    WriteSPI1(dir);    // set direction
    CS=1;
}

/*
 * used to send commands and settings information
 */
void lcdCommand(char command){
    setGPIO(GPIOA_ADDRESS,0x00); // E=0
    Delay10TCYx(0);
    setGPIO(GPIOB_ADDRESS, command); // send data
    Delay10TCYx(0);
    setGPIO(GPIOA_ADDRESS,0x40); // E=1
    Delay10TCYx(0);
    setGPIO(GPIOA_ADDRESS,0x00); // E=0
    Delay10TCYx(0);
}

/*
 * prints out a character to the lcd display
 */
void lcdChar(unsigned char letter){
    setGPIO(GPIOA_ADDRESS,0x80); // RS=1, we going to send data to be displayed
    Delay10TCYx(0); // let things settle down
    setGPIO(GPIOB_ADDRESS,letter); // send display character
    // Now we need to toggle the enable pin (EN) for the display to take effect
    setGPIO(GPIOA_ADDRESS, 0xc0); // RS=1, EN=1
    Delay10TCYx(0); // let things settle down, this time just needs to be long
enough for the chip to detect it as high
    setGPIO(GPIOA_ADDRESS,0x00); // RS=0, EN=0 // this completes the enable pin
toggle
    Delay10TCYx(0);
}

/*
 * the parameter is the position of the cursor according to the HD44780 specs
 * for the lcd display our board has the top row's position range is 01 to
 */
void lcdGoTo(char pos){
    // add 0x80 to be able to use HD44780 position convention
    lcdCommand(0x80+pos);
}

void lcdWriteMessage(rom unsigned char *str){
    while(*str)
        lcdChar(*str++);
}

void lcdWriteVariable(char *str){
    while(*str)
        lcdChar(*str++);
}

//Method to perform an A2D conversion an a specific channel.
void startRead(unsigned char channel)
{
```

```
    ADCON0=(channel<<2);   //Select ADC Channel
    Delay10TCYx(1);
    ADCON0bits.ADON = 1; //Enable ADC.
    sample = 1; //Start conversion.
    while(sample); //Wait for conversion to finish.
    ADCON0bits.ADON = 0; //Disable ADC.
}

//Method to convert float value to string.
void floatToChar(char *str, double num)
{
    int left = (int)(num);
    int right= (int)((num-left) * 1000);
    sprintf(str,"%d.%d",left,right);
}
```

B.2 Sample Code for Prototype Design

```
/*****************************************************************
ANALOG ILLUMINANCE DATA LOGGING
===============================
In this project, a PIC18F8722-type microcontroller is used. The microcontroller is
operated with a 10-MHz crystal.

An SD card is connected to the microcontroller as follows:

SD card - microcontroller
CS      -       RB3
CLK     -       RC3
DO      -       RC4
DI      -       RC5

The program uses the Microchip MDD library functions to read and write to the SD
card recording numerous measurements made by the illuminance sensors.

The sensors are analogue sensors, the result is read every specified time step and
stored in a filed called ANALOG.TXT on an SD card.

Data logging is started when button START/STOP (connected to RB0) is pressed.

Pressing the button for a few seconds during the data collection process will halt
the data collection.

The SD card must only be removed after the data collection is stopped otherwise
the data will be corrupted.

Author: Kevin Smith
Date: 2014
File: LightLogMultipleMuxCont.C
*********************************************************/
#include <p18f8722.h>
#include <spi.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <delays.h>
#include <adc.h>
#include <FSIO.h>

#pragma config WDT = OFF, OSC = HSPLL, LVP = OFF
#pragma config MCLRE = ON,MODE = MC, CCP2MX = PORTC
#define STRT PORTBbits.RB0
#define MuxStrobe PORTEbits.RE0
#define MuxA PORTEbits.RE4
#define MuxB PORTEbits.RE5
#define MuxC PORTEbits.RE6
#define MuxD PORTEbits.RE7

#define NUM(x,y) (10*(x - '0') + y - '0')
#define MSD(x) ((x / 10 + '0'))
#define LSD(x) ((x % 10) + '0')

//Change the number of Mux Assemblies here
#define MuxCount 2 ////////////////////////////////////////////////////////////////

//Change DelayRequired to adjust time between measurement readings!
#define DelayRequired  2 ////////////////////////////////////////////////////////

//Enter the date and time here:
unsigned char DateTime[ ] = "26/08/2014 14:00:00 ";
//////////////////////////////

unsigned char One_Sec_Flag;
unsigned char Days[ ]={0,31,28,31,30,31,30,31,31,30,31,30,31};

void One_Second_Delay(void);
void timer_ISR(void);
```

```
//
// Define the high interrupt vector to be at 0x08
//
#pragma code high_vector=0x08 // Following code at void address 0x08
interrupt(void)
{
    _asm GOTO timer_ISR _endasm // Jump to ISR
}
#pragma code // Return to default code section
//
// timer_ISR is an interrupt service routine (jumps here every 5ms)
//
#pragma interrupt timer_ISR
void timer_ISR( )
{
One_Sec_Flag = 1; // Set One_Sec_Flag
TMR0L = 0x69; // Re-load TMR0
TMR0H = 0x67; // Re-Load TMR0H
INTCON = 0x20; // Set T0IE and clear T0IF
}

//
// This function opens the A/D converter, reads analog data, converts into
// digital and then returns. The required channel number is passed as an
// argument to the function
//
int Read_ADC_Chan(unsigned char chan)
{
    int Res;
        OpenADC(ADC_FOSC_64 & // Open the A/D
        ADC_RIGHT_JUST &
        ADC_0_TAD,
        ADC_CH1 &
        ADC_INT_OFF &
        ADC_VREFPLUS_VDD &
        ADC_VREFMINUS_VSS,
        13);
    Delay10TCYx(10); // Delay for 100 cycles
    SetChanADC(chan); // Select channel
    ConvertADC( ); // Convert
    while(BusyADC( )); // Wait until complete
    Res = ReadADC( ); // Read analog data
    CloseADC( ); // Close A/D
    return Res; // Return the result
}

//
// Configure Timer for 1 second interrupts. Load TIMER registers with
// 16 bit value 26473 = 0x6769
//
void Config_Timer(void)
{
T0CON = 0x87; // 16 bit,Prescaler = 256
TMR0L = 0x69; // Load TMR0L=0x69
TMR0H = 0x67; // Load TMR0H=0x67
INTCON = 0xA0; // Enable TMR0 interrupt
}

//
// This function updates the clock fields.
// 02/10/09 12:00:00
// 01234567890123456
//
void Update_Clock(void)
{
unsigned char day,month,year,hour,minute,second;
day = NUM(DateTime[0], DateTime[1]);
month = NUM(DateTime[3], DateTime[4]);
year = NUM(DateTime[8], DateTime[9]);
hour = NUM(DateTime[11], DateTime[12]);
```

```
minute = NUM(DateTime[14], DateTime[15]);
second = NUM(DateTime[17], DateTime[18]);

second++;
if(second == 60)
{
    second = 0; minute++;
    if(minute == 60)
    {
        minute = 0; hour++;
        if(hour == 24)
        {
            hour = 0; day++;
            if(day == Days[month]+1)
            {
                day = 1; month++;
                if(month == 13)
                {
                    month = 1; year++;
                }
            }
        }
    }
}
DateTime[17] = MSD(second);
DateTime[18] = LSD(second);
DateTime[14] = MSD(minute);
DateTime[15] = LSD(minute);
DateTime[11] = MSD(hour);
DateTime[12] = LSD(hour);
DateTime[8] = MSD(year);
DateTime[9] = LSD(year);
DateTime[3] = MSD(month);
DateTime[4] = LSD(month);
DateTime[0] = MSD(day);
DateTime[1] = LSD(day);
}

void Update_Mux_Select(unsigned char SelectLine)
{
    switch (SelectLine)
    {
        case 0:
            MuxA = 0;
            MuxB = 0;
            MuxC = 0;
            MuxD = 0;
            Delay10TCYx(10); // Delay for 100 cycles
            break;
        case 1:
            MuxA = 1;
            MuxB = 0;
            MuxC = 0;
            MuxD = 0;
            Delay10TCYx(10); // Delay for 100 cycles
            break;
        case 2:
            MuxA = 0;
            MuxB = 1;
            MuxC = 0;
            MuxD = 0;
            Delay10TCYx(10); // Delay for 100 cycles
            break;
        case 3:
            MuxA = 1;
            MuxB = 1;
            MuxC = 0;
            MuxD = 0;
            Delay10TCYx(10); // Delay for 100 cycles
            break;
        case 4:
```

```
        MuxA = 0;
        MuxB = 0;
        MuxC = 1;
        MuxD = 0;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 5:
        MuxA = 1;
        MuxB = 0;
        MuxC = 1;
        MuxD = 0;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 6:
        MuxA = 0;
        MuxB = 1;
        MuxC = 1;
        MuxD = 0;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 7:
        MuxA = 1;
        MuxB = 1;
        MuxC = 1;
        MuxD = 0;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 8:
        MuxA = 0;
        MuxB = 0;
        MuxC = 0;
        MuxD = 1;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 9:
        MuxA = 1;
        MuxB = 0;
        MuxC = 0;
        MuxD = 1;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 10:
        MuxA = 0;
        MuxB = 1;
        MuxC = 0;
        MuxD = 1;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 11:
        MuxA = 1;
        MuxB = 1;
        MuxC = 0;
        MuxD = 1;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 12:
        MuxA = 0;
        MuxB = 0;
        MuxC = 1;
        MuxD = 1;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 13:
        MuxA = 1;
        MuxB = 0;
        MuxC = 1;
        MuxD = 1;
        Delay10TCYx(10); // Delay for 100 cycles
        break;
    case 14:
        MuxA = 0;
```

```
            MuxB = 1;
            MuxC = 1;
            MuxD = 1;
            Delay10TCYx(10); // Delay for 100 cycles
            break;
        case 15:
            MuxA = 1;
            MuxB = 1;
            MuxC = 1;
            MuxD = 1;
            Delay10TCYx(10); // Delay for 100 cycles
            break;
        default:
            MuxStrobe = 1;
            break;

    }

}

void main(void)
{
    FSFILE *pntr;
    int result;
    int count = 0;
    int MuxSelect = 0;
    int MuxCounter = 0;
    int seconds = 0;
    int i[MuxCount] = {0};
    int j[MuxCount] = {0};

    float total[MuxCount] = {0.0};
    float resultADC[MuxCount] = {0.0};
    float mV[MuxCount] = {0.0};
    float Temp;
    unsigned char day2,month2,hour2,minute2,second2;
    unsigned int year2;
//
// Configure PORT RB0 is inout (START/STOP switch and RA1 is the
// analog input where the MCP9701A is connected to
//
    TRISAbits.TRISA1 = 1;
    TRISEbits.RE0=0;
    TRISEbits.RE4=0; //our chip select pin needs to be an output so that we can
toggle it
    TRISEbits.RE5=0;
    TRISEbits.RE6=0;
    TRISEbits.RE7=0;

    TRISFbits.RF1 = 1; // RF1 is input
//////////////////////////////////////////////
    TRISFbits.RF2 = 1; // RF1 is input
    TRISFbits.RF3 = 1; // RF1 is input
    TRISHbits.RH7 = 1; // RF1 is input
//
// Wait until BUTTON is pressed and relesed
//
    One_Sec_Flag = 0;

    while(STRT);
    while(!STRT);

//
// Configure Timer. Start timer interrupts
//
    Config_Timer( );
//
// Look for leap year and adjust for February
//
    result = 10*(DateTime[6] - '0') + DateTime[7] - '0';
    result = result % 4;
```

```
    if(result == 0)
        Days[2] = 29;
    else
        Days[2] = 28;

// Wait until the START/STOP button is pressed and if so enter the Run mode.
    while(STRT);
    while(!STRT);
//
// Initialize MDD library
//
    while(!FSInit( ));
//
// Open file ANALOG.TXT in write mode (create it)
//
    pntr = FSfopenpgm("ANALOG.TXT", "w+");
//
// ========================= START OF LOOP ==========================
//
// Read the sensor values and store in the file
//

while(1)
{
    FSfprintf(pntr, "%s, ", DateTime);

    for(MuxCounter=0; MuxCounter<MuxCount; MuxCounter++)
    {
        for(MuxSelect=0; MuxSelect<16; MuxSelect++)
        {
        // Set all Values to 0 for the next iteration so not interference occurs
            resultADC[0] = 0;
            mV[0] = 0;
            total[0] = 0;
            i[0] = 0;
            j[0] = 0;

        //Configure the Mux Select Lines

            MuxStrobe = 0;
            Update_Mux_Select(MuxSelect);
            Delay1KTCYx (240); // gives a delay of 1000 x 240 x 1/12 = 20 ms

        //Reading Data from sensor(s)

            for(count=0; count<10; count++)
            {
        //Add additional Mux Assemblies here then change #define
MuxCount//////////////
                if(MuxCounter==0)
                {
                    resultADC[0] = Read_ADC_Chan(ADC_CH6); // Get the data RF1
                }
                if(MuxCounter==1)
                {
                    resultADC[0] = Read_ADC_Chan(ADC_CH7); // Get the data RF2
                }
                if(MuxCounter==2)
                {
                    resultADC[0] = Read_ADC_Chan(ADC_CH8); // Get the data RF3
                }
                if(MuxCounter==3)
                {
                    resultADC[0] = Read_ADC_Chan(ADC_CH15); // Get the data RH7
                }

                mV[0] = resultADC[0] * 3300.0 / 1024.0; // Convert to mV
                total[0] += mV[0];
            }

                total[0] /= 10.0;
```

```
                i[0] = (int)total[0]; // Integer part
                j[0] = (int)(((total[0])-(i[0]))*10); // Fractional part
        //
        // Write to SD card
        //
                FSfprintf(pntr, "%d.%d, ", i[0], j[0]);
        }
    }

    FSfprintf(pntr, "\n");


// Check if BUTTON is pressed and if so, close the file and stop the program
//
    if(STRT == 0)
    {

// Set date and time values for the File Modified Date

        day2 = NUM(DateTime[0], DateTime[1]);
        month2 = NUM(DateTime[3], DateTime[4]);
        year2 = 1000*(DateTime[6]-'0') + 100*(DateTime[7]-'0') + 10*(DateTime[8]-
'0') + 1*(DateTime[9]-'0');
        hour2 = NUM(DateTime[11], DateTime[12]);
        minute2 = NUM(DateTime[14], DateTime[15]);
        second2 = NUM(DateTime[17], DateTime[18]);
        SetClockVars(year2, month2, day2, hour2, minute2, second2);

        FSfclose(pntr);
        while(1);
    }
//
// Wait for a second. Variable "flag" is set whenever an interrupt occurs
//
    for(seconds=0; seconds<DelayRequired; seconds++)
    {
        while(!One_Sec_Flag);
        One_Sec_Flag = 0;
        Update_Clock( );
    }

}
}
```

APPENDIX C: MATLAB CODE

C.1 Example Matlab Code For Visual Representation of 16 Sensor Data

```
%For 16 Sensor locations:
clc
close all
clear all

%Define number of data recordings
DataCount = 1;
Count = 1;
Start = 27;

%A, x and y are vectors containing sample points and data
x = [-0.75, -0.25, 0.25, 0.75, -0.75, -0.25, 0.25, 0.75, -0.75, -
0.25, 0.25, 0.75, -0.75, -0.25, 0.25, 0.75];
y = [0.75, 0.75, 0.75, 0.75, 0.25, 0.25, 0.25, 0.25, -0.25, -0.25,
-0.25, -0.25, -0.75, -0.75, -0.75, -0.75];


[xq, yq] = meshgrid(-1:0.025:1, -1:0.025:1);

for i = 1:DataCount


A=xlsread('Test16.xlsx','M27LUX',strcat('B',num2str(i+27),':R',num
2str(i+27)));
    B = A(1);
    C = A(2:end);

    %Define a regular grid and interpolate the data over the grid
    Cq = griddata(x,y,C,xq,yq, 'natural');

    %Plot the gridded data
    pause(0.1);
    surf(xq,yq,Cq);
    shading interp
    %title(strcat('Timestamp : ' , num2str(B(1))))
    %Alter the view of the plotted data eg([0 90]) is 2D from top
    view([0 90]);
    axis square
    h.YTick = [-1,-0.5,0,0.5,1];
    h.XTick = [-1,-0.5,0,0.5,1];
    caxis([0 , 1500]);
    set(gcf, 'renderer', 'zbuffer');
    colorbar;
    h = colorbar;
    title(h, 'Illuminance (lux)');

end
```

C.2 Example Matlab Code For Visual Representation of 64 Sensor Data

```
%For 64 Sensor locations:
clc
close all
clear all

%Define number of data recordings
DataCount = 1;
Start = 46;
Count = 1;
%A, x and y are vectors containing sample points and data
x = [-0.875, -0.625, -0.375, -0.125, 0.125, 0.375, 0.625, 0.875,
...
    -0.875, -0.625, -0.375, -0.125, 0.125, 0.375, 0.625, 0.875,
...
    -0.875, -0.625, -0.375, -0.125, 0.125, 0.375, 0.625, 0.875,
...
    -0.875, -0.625, -0.375, -0.125, 0.125, 0.375, 0.625, 0.875,
...
    -0.875, -0.625, -0.375, -0.125, 0.125, 0.375, 0.625, 0.875,
...
    -0.875, -0.625, -0.375, -0.125, 0.125, 0.375, 0.625, 0.875,
...
    -0.875, -0.625, -0.375, -0.125, 0.125, 0.375, 0.625, 0.875,
...
    -0.875, -0.625, -0.375, -0.125, 0.125, 0.375, 0.625, 0.875];

y = [0.875, 0.875, 0.875, 0.875, 0.875, 0.875, 0.875, 0.875, ...
    0.625, 0.625, 0.625, 0.625, 0.625, 0.625, 0.625, 0.625, ...
    0.375, 0.375, 0.375, 0.375, 0.375, 0.375, 0.375, 0.375, ...
    0.125, 0.125, 0.125, 0.125, 0.125, 0.125, 0.125, 0.125, ...
    -0.125, -0.125, -0.125, -0.125, -0.125, -0.125, -0.125, -
0.125, ...
    -0.375, -0.375, -0.375, -0.375, -0.375, -0.375, -0.375, -
0.375, ...
    -0.625, -0.625, -0.625, -0.625, -0.625, -0.625, -0.625, -
0.625, ...
    -0.875, -0.875, -0.875, -0.875, -0.875, -0.875, -0.875, -
0.875];

[xq, yq] = meshgrid(-1:0.025:1, -1:0.025:1);

for i = 1:DataCount

    A =
xlsread('Test64.xlsx','T20LUX',strcat('B',num2str(i+Start),':BN',n
um2str(i+Start)));
    B = A(1);
    C = A(2:end);
    %Define a regular grid and interpolate the data over the grid

    Cq = griddata(x,y,C,xq,yq, 'natural');
```

```
    %Plot the gridded data
    pause(0.1);
    surf(xq,yq,Cq);
    shading interp
    %hSurf =
surf(xq,yq,Cq,'EdgeColor','none','LineStyle','none','FaceLighting'
,'phong');
    %title(strcat('Timestamp : ' , num2str(B(1))))
    %Alter the view of the plotted data eg([0 90]) is 2D from top
    view([0 90]);
    axis square
    h.YTick = [-1,-0.5,0,0.5,1];
    h.XTick = [-1,-0.5,0,0.5,1];
    caxis([0 , 1500]);
    set(gcf, 'renderer', 'zbuffer');
    colorbar;
    h = colorbar;
    title(h, 'Illuminance (lux)');

end
```

APPENDIX D: EXCEL EXTRACTS

D.1 Sample Excel Spreadsheet for Sensor Testing Results

Table 8: Sample of Raw Data collected from Sharp Sensor Tests

Data Collection Set 1:						
Number	Current :	Control (SDL400)	Sharp 1	Sharp 2	Sharp 3	Sharp 4
1	10,40	104,00	48,44	45,21	48,44	48,44
2	11,20	163,00	67,81	64,58	67,81	67,81
3	12,20	243,00	103,33	100,10	103,33	106,56
4	13,20	330,00	138,85	135,62	138,85	142,79
5	14,10	426,00	184,55	177,60	180,83	184,55
6	15,10	524,00	226,35	219,58	226,35	226,35
7	16,10	621,00	271,24	258,32	264,78	268,64
8	17,20	721,00	313,22	300,30	309,99	313,22
9	18,00	810,00	351,97	335,81	345,50	348,73
10	19,10	928,00	397,18	381,28	393,95	397,18
11	20,50	1048,00	448,83	432,69	445,60	452,69
12	21,10	1128,00	487,58	464,99	477,89	484,36
13	22,10	1212,00	516,64	500,50	513,42	519,87
14	23,20	1329,00	561,85	542,48	558,62	565,86
15	25,30	1438,00	619,97	594,15	610,29	619,97
16	26,80	1548,00	661,95	639,35	652,27	665,18
17	28,60	1648,00	716,84	684,56	703,93	713,61
18	29,30	1710,00	739,44	707,15	723,30	736,22
19	30,40	1775,00	758,82	732,99	745,91	758,82
20	31,30	1817,00	791,11	752,37	774,96	784,66
21	33,50	1918,00	829,87	797,57	816,94	829,87
22	34,70	2000,00	862,16	829,87	849,23	858,92

D.2 Sample Excel Spreadsheet for Manipulated Sensor Testing Results

Table 9: Sample of Manipulated Data collected from Sharp Sensor Tests

Data Manipulated Set 1:									
Linear Offsets		**2.32035715**							
No:	Current :	Control (SDL400)	Sharp 1	Sharp 2	Sharp 3	Sharp 4	Max Lux Error	% Lux Error Max	Lux Range
1	10.40	104	112.39	104.89	112.39	112.39	8.39	8.06	7.49
2	11.20	163	157.34	149.86	157.34	157.34	13.14	8.06	7.49
3	12.20	243	239.76	232.27	239.76	247.25	10.73	4.42	14.99
4	13.20	330	322.18	314.68	322.18	331.32	15.32	4.64	16.63
5	14.10	426	428.22	412.08	419.58	428.22	13.92	3.27	16.14
6	15.10	524	525.20	509.49	525.21	525.21	14.51	2.77	15.71
7	16.10	621	629.37	599.39	614.38	623.34	21.61	3.48	29.98
8	17.20	721	726.78	696.80	719.28	726.78	24.20	3.36	29.97
9	18.00	810	816.69	779.21	801.69	809.19	30.79	3.80	37.48
10	19.10	928	921.59	884.71	914.10	921.59	43.29	4.67	36.88
11	20.50	1048	1041.45	1003.99	1033.96	1050.39	44.01	4.20	46.40
12	21.10	1128	1131.36	1078.94	1108.88	1123.88	49.06	4.35	52.43
13	22.10	1212	1198.80	1161.34	1191.32	1206.28	50.66	4.18	44.94
14	23.20	1329	1303.69	1258.75	1296.20	1313.00	70.25	5.29	54.25
15	25.30	1438	1438.56	1378.64	1416.10	1438.56	59.36	4.13	59.92
16	26.80	1548	1535.97	1483.51	1513.50	1543.46	64.49	4.17	59.95
17	28.60	1648	1663.33	1588.42	1633.37	1655.83	59.58	3.62	74.91
18	29.30	1710	1715.77	1640.84	1678.32	1708.29	69.16	4.04	74.93
19	30.40	1775	1760.74	1700.79	1730.78	1760.74	74.21	4.18	59.94
20	31.30	1817	1835.65	1745.77	1798.19	1820.69	71.23	3.92	89.88
21	33.50	1918	1925.60	1850.64	1895.60	1925.60	67.36	3.51	74.96
22	34.70	2000	2000.52	1925.60	1970.51	1993.00	74.40	3.72	74.92
							74.40	**8.06**	**89.87**

D.3 Raw Data Sensor Testing Results

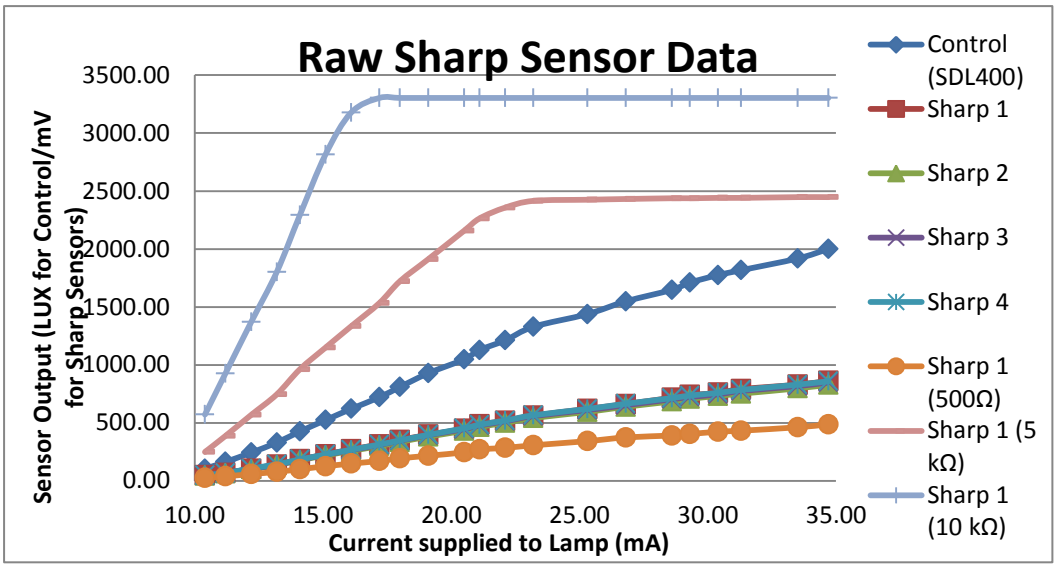


Figure 52: Raw Test Data for Sharp Sensors

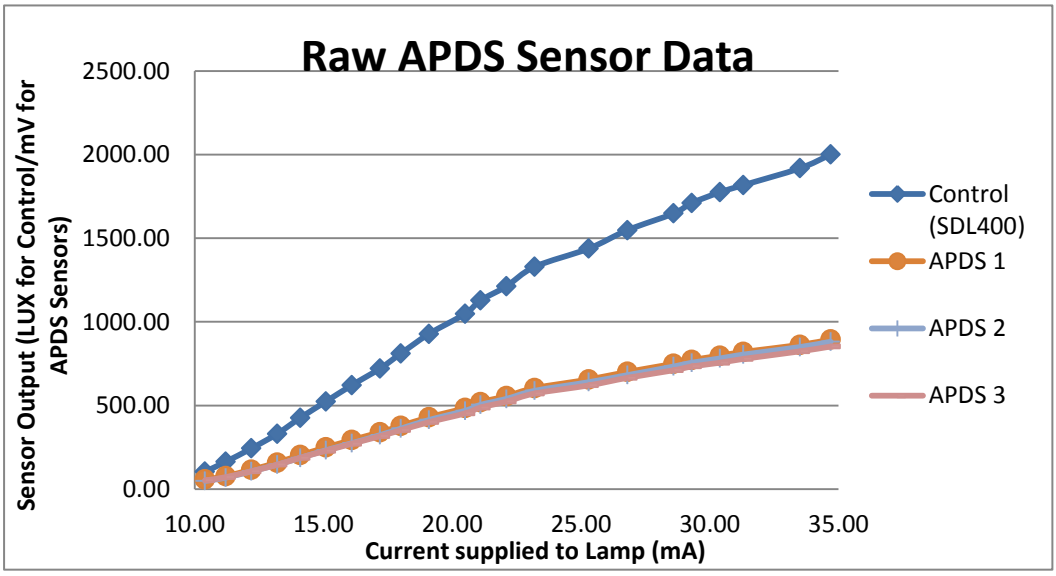


Figure 53: Raw Test Data for APDS Sensors

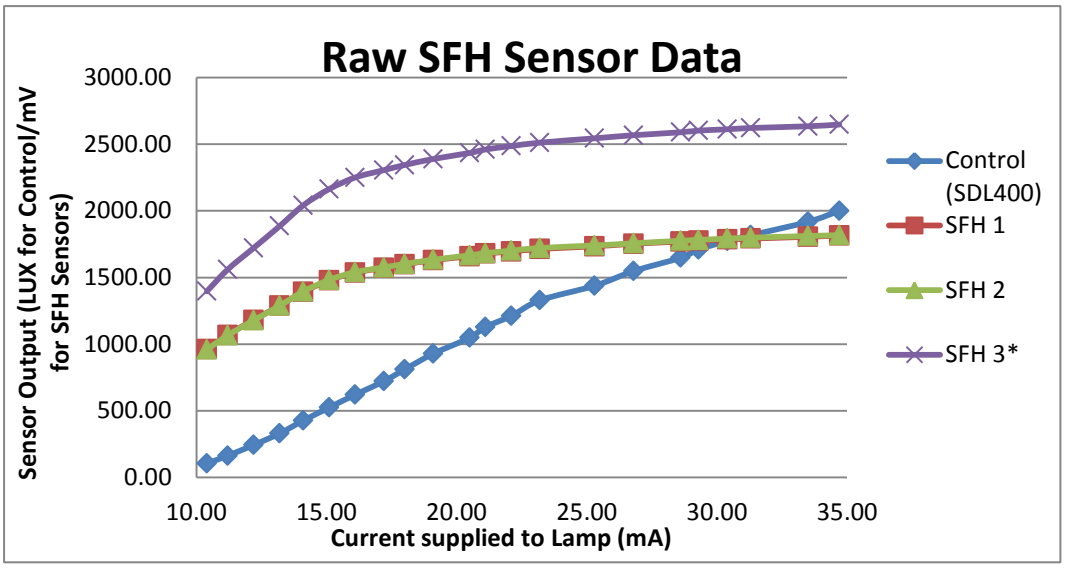


Figure 54: Raw Test Data for SFH Sensors

D.4 Manipulated Data Sensor Testing Results

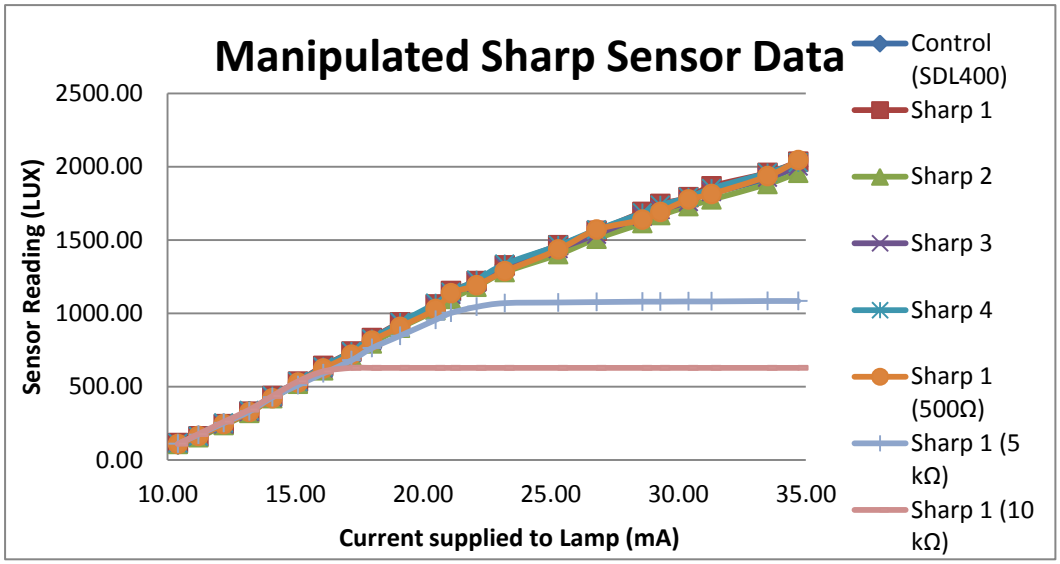


Figure 55: Manipulated Test Data for Sharp Sensors

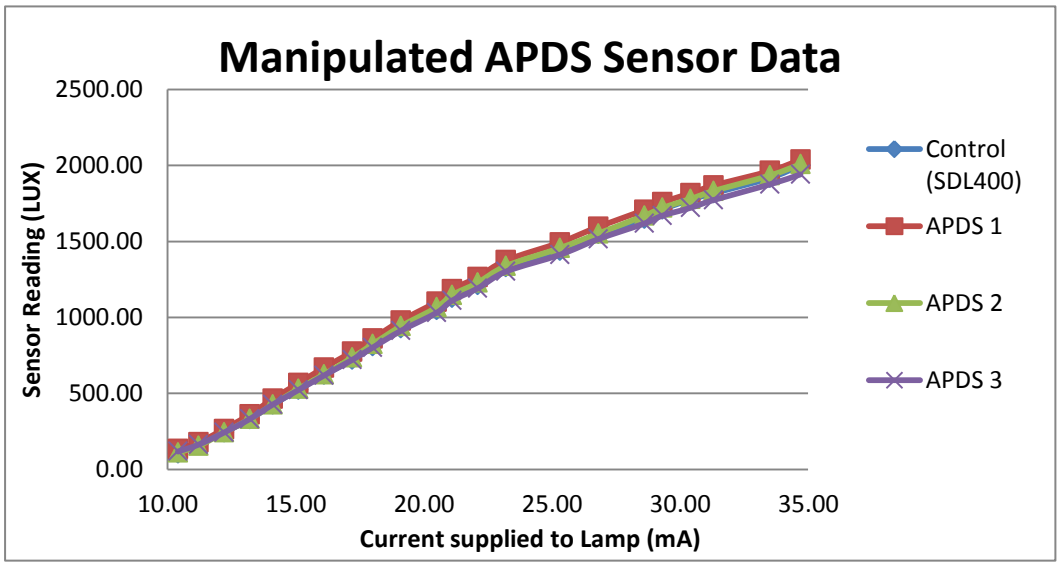


Figure 56: Manipulated Test Data for APDS Sensors

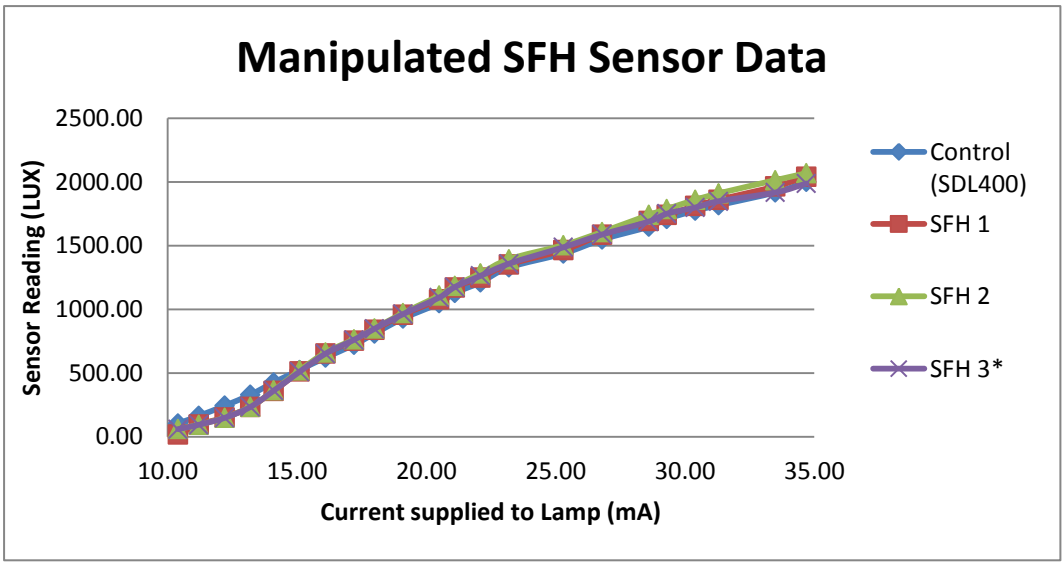


Figure 57: Manipulated Test Data for SFH Sensors

D.5 Sample Extracts From Excel Spreadsheet Created During Prototype 16 Testing

Table 10: Unprocessed Test Data for 16 Sensor Prototype

Timestamp		Sensor															
		1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00
21/10/2014	09:30:00	195.9	160.1	203.9	154.6	228.8	240.7	228.1	209.4	296.8	321.6	793.4	257.1	458.2	300.6	902.9	221.7
21/10/2014	09:35:00	237.5	166.2	222.6	156.9	242.6	265.8	324.8	219.7	314.8	323.8	704.1	279.7	349.9	327.7	532.3	231.3
21/10/2014	09:40:00	376	170.4	209.1	160.4	245.5	296.1	384.1	226.8	315.8	328	487.2	327.7	325.4	338	383.4	251
21/10/2014	09:45:00	632.2	174.3	217.8	164.6	247.5	318.3	398.9	246.8	317.7	342.8	438.6	381.8	408.9	340.3	361.2	256.8
21/10/2014	09:50:00	954.8	186.9	223	169.1	274.2	314.5	408.3	238.4	327.4	360.6	330.6	510.7	376.4	358.6	360.2	272.6
21/10/2014	09:55:00	689.3	211.7	232.6	176.6	333.8	304.8	347	246.8	362.5	372.8	361.5	512.4	408.9	362.8	409.9	304.8
21/10/2014	10:00:00	351.5	290.6	351.5	188.5	440.2	292.9	358.3	252.3	461.4	408.9	465	540.1	397	364.4	348.6	330.9
21/10/2014	10:05:00	382.5	259.7	264.9	200.7	342.2	274.8	335.1	255.2	460.1	448.2	461.8	566.8	415.4	369.6	350.3	371.2
21/10/2014	10:10:00	433.7	300	290	225.9	352.2	267.4	354.1	275.2	431.5	547.2	434.7	596.5	473.4	388.6	348	378.9
21/10/2014	10:15:00	373.8	309.3	370.6	255.5	611.6	273.2	612.3	350.3	537.8	687.3	529.4	688.3	567.1	411.5	356.1	397.6
21/10/2014	10:20:00	355.7	334.1	317.1	282.9	467.9	269.7	469.5	266.5	507.5	764.4	509.5	763.1	786.3	431.1	792.1	431.5
21/10/2014	10:25:00	336.7	393.8	307.4	290.3	364.8	263.9	313.2	542	584.5	730.8	583.9	731.2	884.9	455	885.9	466.9
21/10/2014	10:30:00	344.8	497.2	344.1	355.7	847.8	258.4	851.1	257.8	639	635.1	638.7	630	871	479.8	382.5	480.4

Table 11: Processed Test Data for 16 Sensor Prototype

0.63211207	Sensor															
Timestamp		1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00
21/10/2014	09:30:00	124	101	129	98	145	152	144	132	188	203	502	163	290	190	571	140
21/10/2014	09:35:00	150	105	141	99	153	168	205	139	199	205	445	177	221	207	336	146
21/10/2014	09:40:00	238	108	132	101	155	187	243	143	200	207	308	207	206	214	242	159
21/10/2014	09:45:00	400	110	138	104	156	201	252	156	201	217	277	241	258	215	228	162
21/10/2014	09:50:00	604	118	141	107	173	199	258	151	207	228	209	323	238	227	228	172
21/10/2014	09:55:00	436	134	147	112	211	193	219	156	229	236	229	324	258	229	259	193
21/10/2014	10:00:00	222	184	222	119	278	185	226	159	292	258	294	341	251	230	220	209
21/10/2014	10:05:00	242	164	167	127	216	174	212	161	291	283	292	358	263	234	221	235
21/10/2014	10:10:00	274	190	183	143	223	169	224	174	273	346	275	377	299	246	220	240
21/10/2014	10:15:00	236	196	234	162	387	173	387	221	340	434	335	435	358	260	225	251
21/10/2014	10:20:00	225	211	200	179	296	170	297	168	321	483	322	482	497	273	501	273
21/10/2014	10:25:00	213	249	194	184	231	167	198	343	369	462	369	462	559	288	560	295
21/10/2014	10:30:00	218	314	218	225	536	163	538	163	404	401	404	398	551	303	242	304

APPENDIX E: TEXT FILE EXTRACTS

E.1 Sample Extract From .txt File Created During Prototype 16 Testing

```
13/10/2014 09:30:00 , 195.9, 160.1, 203.9, 154.6,
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349.9, 327.7, 532.3, 231.3,
13/10/2014 09:40:00 , 376.0, 170.4, 209.1, 160.4,
245.5, 296.1, 384.1, 226.8, 315.8, 328.0, 487.2, 327.7,
325.4, 338.0, 383.4, 251.0,
13/10/2014 09:45:00 , 632.2, 174.3, 217.8, 164.6,
247.5, 318.3, 398.9, 246.8, 317.7, 342.8, 438.6, 381.8,
408.9, 340.3, 361.2, 256.8,
13/10/2014 09:50:00 , 954.8, 186.9, 223.0, 169.1,
274.2, 314.5, 408.3, 238.4, 327.4, 360.6, 330.6, 510.7,
376.4, 358.6, 360.2, 272.6,
13/10/2014 09:55:00 , 689.3, 211.7, 232.6, 176.6,
333.8, 304.8, 347.0, 246.8, 362.5, 372.8, 361.5, 512.4,
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440.2, 292.9, 358.3, 252.3, 461.4, 408.9, 465.0, 540.1,
397.0, 364.4, 348.6, 330.9,
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567.1, 411.5, 356.1, 397.6,
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467.9, 269.7, 469.5, 266.5, 507.5, 764.4, 509.5, 763.1,
786.3, 431.1, 792.1, 431.5,
13/10/2014 10:25:00 , 336.7, 393.8, 307.4, 290.3,
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884.9, 455.0, 885.9, 466.9,
13/10/2014 10:30:00 , 344.8, 497.2, 344.1, 355.7,
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871.0, 479.8, 382.5, 480.4,
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E.2 Sample Extract From .txt File Created During Prototype 64 Testing

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1475.0, 697.7, 1174.9, 1187.2, 387.6, 1991.2, 490.4, 514.3,
703.1, 651.2, 794.0, 2412.8, 431.1, 504.6, 798.2, 750.5,
524.6, 503.3, 523.0, 2409.9, 1325.1, 2331.2, 647.7, 663.2,
360.2, 602.9, 553.3, 453.7, 2410.5, 2409.5, 2397.6, 2342.5,
572.6, 654.1, 498.5,
19/11/2014 10:35:00, 191.4, 187.5, 2404.1, 346.1, 194.9,
173.0, 173.3, 151.7, 252.6, 2395.7, 315.8, 224.6, 237.8,
241.3, 184.9, 158.2, 2403.7, 340.3, 246.2, 213.0, 242.0,
454.0, 611.6, 520.7, 2418.6, 332.5, 259.7, 401.2, 499.8,
1129.8, 760.5, 685.1, 2420.5, 385.4, 2031.5, 506.6, 1412.1,
640.9, 764.0, 548.1, 2403.4, 451.1, 503.3, 599.7, 777.6,
559.1, 507.2, 520.1, 2411.8, 991.2, 1048.0, 396.0, 698.0,
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245.5, 179.1, 158.8, 2387.3, 2388.9, 257.8, 211.0, 262.6,
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465.3, 571.6, 560.0, 339.9, 2411.1, 2419.5, 1622.2, 1852.3,
769.2, 550.7, 2384.1,
19/11/2014 10:45:00, 196.5, 194.0, 246.2, 2377.0, 234.6,
171.1, 172.4, 152.7, 247.1, 2349.9, 387.0, 229.1, 232.6,
238.1, 181.1, 150.1, 2290.3, 2124.0, 254.2, 207.8, 248.4,
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885.9, 565.2, 628.4,
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232.6, 188.2, 154.0, 449.2, 2413.7, 295.8, 211.0, 237.5,
461.1, 548.4, 883.9, 2383.1, 428.9, 234.6, 303.2, 500.8,
879.1, 841.4, 1103.4, 2407.0, 348.0, 2024.7, 433.1, 705.1,
704.7, 712.2, 452.7, 2009.6, 792.1, 464.0, 600.0, 2018.6,
540.1, 544.9, 522.3, 427.6, 2409.5, 541.0, 279.7, 2390.2,
459.2, 540.4, 580.7, 299.3, 528.8, 2416.3, 1116.9, 2400.8,
836.6, 1593.2, 549.1,
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APPENDIX F: SENSOR DEVICE SUMMARY

F.1 Summary of Various Illuminance Sensing Devices and their Characteristics

Table 12: Summary of Various Illuminance Sensing Devices and their Characteristics

	APDS-9004-020	APDS-9005-020	GA1A2S100LY	ISL29001IROZ-T7	SFH 5711	SFH 7770	GL5528
Cost/unit*	R8.14	R6.43	R11.20	R30.35	R18.31	R15.33	
Spectral Response	Close to that of the human eye	Close to that of the human eye	Similar to that of the human eye	Matched to that of the human eye	Perfect match to Human Eye Sensitivity	Well matched to the human eye	
Peak Sensitivity	620nm	500nm	555nm	540nm	555nm	555nm	540nm
Size	1.1x3.2x1.6 (mm)	0.55x1.6x1.5 (mm)	1.8x3.0x4.0 (mm)	0.75x2.5x2 (mm)	1.25x2.35x 2.95(mm)	0.9x2.8x2.8 (mm)	2.4x4.3x5.1 (mm)
Local Availability	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Toxicity	RoHS compliant, Lead Free	RoHS compliant, Lead Free	Compliant with RoHS directive, Lead-free	Pb-Free, RoHS compliant	Pb-Free	Lead (Pb) Free, RoHS Compliant	RoHS Compliant
Output A/D	Analogue	Analogue	Analogue	Digital	Analogue	Analogue	Analogue
Response Curve	Good Output Linearity	Output Linearity	Linear Output		logarithmic output	High linearity	
Mounting Type	Reverse Surface Mount	Surface Mount	Through- Hole	Surface Mount	Surface Mount	Surface Mount	Through-Hole
Component Type	ChipLED	ChipLED	Integrated photodiode and signal processing circuit	Photodiode with IR rejection	Opto Photodiode hybrid	Opto Photodiode hybrid	Photoresistor
Range (lux)	10-1000	10-1000	10-10000	0.3-10000	3-80000	3-65000	1-100

*Cost per unit quoted on 9/4/2013.